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WEST INDIAN BULLETIN

VOLUME XIX.

THE BROWN HARD-BACK GRUB IN ANTIGUA.

(*LACHNOSTERNA ANTIGUAE*, ARROW.)

BY H. A. BALLOU, M.Sc.,

Entomologist on the Staff of the Imperial Department of Agriculture for the West Indies.

The brown hard-back grub in Antigua appears to have been entirely unknown as a pest until somewhere about 1911, when attention began to be drawn to it. At first it was noticed only in connexion with the failure of sugar-cane cuttings to grow when planted, and afterwards it was observed in connexion with growing and ripening canes that were diseased, or stunted, or that entirely died out. At the end of 1911, a field of onions of about 7 acres was entirely destroyed by this insect, and since then it has been recognized also as a pest of Indian corn, sweet potatoes, and yams.

When attention was first directed to this insect in cane fields, it was never found in any considerable numbers, but it was always associated with canes that were in a condition to attract attention. In the case of the young plants, it will be realized that a very few grubs in the soil about a cane cutting

would be sufficient to prevent a development of healthy roots and shoots, but when only a few grubs occurred in the soil at the roots of a large well-grown cane, it would not appear that they were sufficient to cause any considerable amount of injury. In the case of a crop like Indian corn and onions, it was very easy to associate the presence and feeding of these soil grubs with the injury to the crops.

Previous to the discovery of hard-back grubs in the soils in Antigua, root disease of sugar-cane was well known to the planters. This was attributed to the attacks of the fungus *Marasmius Sacchari.*

This root disease was known to be definitely related to what might be called bad agriculture and unfavourable conditions. The bad agriculture had resulted from the situation which existed during the depression of the sugar industry, when money was scarce and the land was starved, and the canes were being grown in a soil lacking in tilth, suffering for want of an abundance of coarse organic manures, all of which factors, acting together, produced a compacted soil in which the ordinary estate drainage was insufficient in times of excessive rainfall, and which suffered, also in direct consequence of these conditions, in times of prolonged drought.

Much improvement has been brought about in Antigua as a result of better cultural methods during the past twenty years, but there is a tendency at the present time in certain localities to refer to grub attacks as being responsible for the condition of sugar-cane, when they present the typical appearance known for so long as root disease. There is no doubt that the destruction of the roots by insects would produce the same effect in the general appearance of a plant as if the roots were destroyed by a fungus, or as if they had been killed by asphyxiation resulting from insufficient drainage, or from the effects of drought. In those cane fields where the brown hard-back grub attacks the sugar-cane roots, this insect probably contributes, and perhaps contributes in some considerable degree, to produce the condition referred to as root disease. At the present time, however, there is no indication of the extent to which insect injury contributes to this result, and until agricultural methods in Antigua have done away to a very considerable extent with other influences which produce the root disease condition, it will not be possible to say how much of the injury is due to the attack of these insects. It seems certain that in some cases the feeding of the number of insects that are found in the soils of sugar-cane fields must cause injury to the canes, but there are some surprising anomalies indicated by the investigations that have been carried out up to the present time. Hard-back grubs have been found in great abundance in the soil about the roots of badly diseased canes, but in nearly every instance there have been other conditions which might well have caused all the injury to the canes, and in other cases the number of grubs found at the roots of canes which appeared to be in perfect health, showing no sign of disease or unfavourable environmental condition, have been so great as to cause wonder that no injury was apparent.

There would appear to have been a general development of soil grubs as pests of sugar-cane in different parts of the world within the past few years. In Barbados, the attacks of the root borer (*Diaprepes abbreviatus*) attracted attention in 1910, and at that time improved cultural methods were recommended for the control of this insect, and in one instance at least where these recommendations have been carefully followed, an estate which suffered badly from root borer attacks in 1910 and 1911, has since that time been entirely free from such attacks. Much attention has been given to this pest, and in connexion with this work, the Barbados brown hard back (*Phytalus smithi*) has come into some prominence. Up to the present time, however, Barbados planters do not seem to have formed any precise opinion as to the amount of damage that is being done in fields of sugar-cane by the brown hard-back.

In the annual reports of the Barbados Department of Agriculture, and the report on the sugar-cane experiments in Barbados, references are to be found to the injuries caused by the root borer and hard-back grubs to the sugar canes grown in the experimental plots, where they have occurred in such numbers as to be considered as having seriously interfered with the results of the experiments. The references to the root borer grubs in the experiment plots are to be found in each report from 1912 to the present time, while the hard-back grubs are referred to only from 1914 on.

In Mauritius, *Phytalus smithi* has been known as a serious pest in sugar cane fields since 1911. In that colony considerable sums of money have been spent, and legislation has been enacted by the Government for the control of this insect, and to prevent its spread.

In St. Kitts, the brown hard back (*Lachnosterna patruelis*) was discovered in 1912, and, while it has not occurred in great numbers, there has been a tendency on the part of some planters to refer to the attacks by this insect as explaining a diseased condition in sugar-cane.

In recent years also, other soil grubs, closely related to and of similar habits to these brown hard-back grubs have attracted greatly increased attention in Porto Rico, in the United States, in Canada, and in Australia.

So far as these insects have been observed in the Lesser Antilles, they have not been responsible for any characteristic appearance or condition of growing sugar-cane ; but in Mauritius, where it is reported that entire fields of growing canes are entirely killed out, and in Australia, where root injury is said to be so severe that strong, well-developed canes are blown over in heavy winds, there would seem to be very definite forms of injury to be ascribed to these pests.

The knowledge so far obtained of the brown hard back in Antigua has been derived from the observations by Dr. Tempany, when Superintendent of Agriculture for the Leeward Islands ; of the present writer during brief visits in 1911, '12, '14, '16, '19, and a more extended one of several weeks in 1920 ; and of those of Mr. E. S. Eldridge in 1919 and 1920.

After the visit of the writer to Antigua in March 1919, arrangements were made for Mr. Eldridge, then second assistant on the Staff of the Botanic and Experiment Station, to pay weekly visits to the estate in that island where most of the observations on this insect had been made. This estate is referred to in this paper as estate A. Mr. Eldridge also worked with the writer during the 1920 visit, and in addition has made a number of interesting observations on the life-history of the insect, both in captivity and in the field, all of which are made use of in the preparation of this paper.

The examinations by Mr. Eldridge on his weekly visits were made in three cane fields regularly—one of plant canes, one of first ratoons, and one of second ratoons. In each of these fields a hole 2 feet square was dug in a bank, a similar hole in a bar, and an unhealthy plant was dug up in each field on each visit. The soil taken from these holes, and at the base of the cane plant that was removed, was carefully examined, and a record made as to the number of brown hard backs found, whether as grubs, pupae, adults or eggs; and in the case of the larvae, notes were made on the size, and on their general condition. These weekly visits commenced on May 20, 1919, and extended to January 2, 1920.

In the field of plant canes, the number of examinations made was twenty-five, and altogether 264 grubs were found. Of these, 148 or 56 per cent. were found under the unhealthy plant, and 116 or 44 per cent. were found in the soil of the bank and bar. Under the plant, which was an unhealthy plant in its general appearance, the numbers of insects found ranged from none to fifteen. In twenty instances of the twenty-five, the number was less than ten.

In the field of first ratoons twenty-six examinations were made, a total of 734 insects being discovered, of which 425 or 58 per cent. were found under the unhealthy plants, the numbers ranging from none to thirty for each plant. In this field, 309 insects or 42 per cent. were found under the bank and bar.

In the field of second ratoons, in twenty-seven such examinations there were found altogether 849 of these insects, the number under the plant being 552 or 65 per cent. of the total, the numbers ranging from none to sixty under each plant. Of those found in the other situations in this field, twenty-seven or 15 per cent. were in the bank and 20 per cent. in the bar, the numbers in these situations ranging from none to thirty.

The figures relating to the number of grubs taken from the soil under and about the unhealthy plants in these three fields are the ones of interest at the present moment. For instance, in the case of the twenty-five unhealthy plants dug up and examined in the field of plant canes, it would not appear that there was in any instance a sufficient number of grubs present to account for very serious injury to a stool of healthy and vigorous sugar-cane, and in those instances where there was less than ten grubs per cane stool, it is hardly to be expected that their feeding would have had any appreciable affect on the condition of the canes. In the case of the twenty-five unhealthy plants examined in the first ratoon fields, no grubs were found at the base of four of them,

three others had less than ten, and in the case of thirteen others the numbers ranged from ten to twenty, and in the case of five the numbers are over twenty, with thirty as a maximum.

In the case of three of these unhealthy plants in the second ratoon field, no grubs were found, six gave less than ten each, six others twenty or under, while the remainder ranged up to a maximum of sixty each.

During the writer's visit—January- March 1920—the examinations of the soil in connexion with the grub examination was made by digging out the entire cane hole on an area occupied by a stool of canes and down to the subsoil, or as far as grubs or pupae were found, so that in a field where the lining was 4½ by 4½ feet, each cane hole examined meant the digging out of an area 4½ by 4½ feet. In recording the hard backs found, they are counted as grubs, pupae and adults, and the total is given as the number of grubs or insects found, on the supposition that whether grubs, pupae or adults at the time of the examination, they had all been grubs during the season, and had presumably all exercised some influence on the condition of these canes.

The number of these examinations made amounted to about 120, in addition to examination in the banks of young canes and corn fields, where the more extended examination was not considered feasible or necessary.

It would be of interest to consider some of the results of examinations in these three fields in which Mr. Eldridge carried out his series of observations during the year These were the fields of plant canes, first ratoons, and second ratoons, which may for the present be designated as fields A, B, and C, respectively.

Before proceeding with the study of the soil conditions, the writer obtained a statement from the manager of the estate as to the area of the field, the nature of the soil, and the susceptibility of the canes in each field to grub attack This information with regard to these three fields is given.

Field A. Plant Canes This is a field of 9½ acres. The soil is described as a heavy soil, with a clay subsoil Grubs are said to be always bad in this field in patches, especially in ratoons. Root disease has the same occurrence and distribution as the grubs.

In this field a very good strong stool of canes, with practically no root disease, standing on the edge of a field trench, and containing seventeen good canes in the clump, gave five grubs, fifteen pupae, and two adults, a total of twenty-two, all of which were found directly under the plant.

Another stool of canes, which was considered an average stool for the field and in which there were eleven good canes, and with some indication of the presence of root disease, gave ten grubs and four pupae, a total of fourteen, as against the twenty-two found under a much stronger and better stool.

Field B. 1st. Ratoons. This is a field of 4½ acres. The soil in this field is described as being very heavy. Root disease and grubs were very bad here in the 1917 ratoon crop, and also are bad in the ratoon crop to be reaped in 1920.

In this field three examinations were made ; one good stool in a healthy patch of canes gave thirty-one grubs and three pupae, a total of thirty-four. At the next examination in the same field, two holes were taken together, and the examination of the soil here gave thirty-three grubs and one pupae, a total of thirty-four from two cane holes of very bad canes attacked by root disease, the canes themselves being small with nothing to cut for reaping, and some of the shoots actually dying.

Field C. 2nd Ratoons. This is a field of 6 acres. The soil is described as being light, with marly subsoil. 'It is fairly easily drained, and is never badly attacked by grubs.'

In this field seventeen cane hole examinations were made. Eight of these were in what was said to be good average canes, but the canes in this part of the field had been cut before the examination. However, the appearance of the stumps when seen a few days after the canes were cut, indicated that the conditions were not at all bad. The first four cane holes were taken in a block ; four consecutive holes in the same row. From this block were taken a total of 199 brown hard backs consisting of 152 grubs, forty five pupae, and two adults. The next four were taken in the same row with intervals of about 30 feet. These gave the following : the first eighty-seven grubs and four pupae, the second seventy grubs and nine pupae, the next eighty-six grubs and four pupae, and the last thirty-five grubs and six pupae, a total of 319 insects, or an average of about eighty per cane hole. If these eight cane holes are taken together, the total number of insects would be 518, or an average of nearly sixty-five per cane hole, in a portion of the field where the canes were good for second ratoons.

The next examination consisted of two cane holes in which the canes were very bad, in the midst of a fairly bad root disease patch. The spot was selected on the edge of the canes that were still standing. One of these gave twenty-six grubs and two pupae, and the other seventy-four grubs and four pupae, the totals being twenty-eight and seventy-eight, as compared with the much higher numbers found in that part of the field where the canes had been much better.

The next six cane holes examined were chosen in the healthiest part of the field where the canes were still standing. This spot was on the western side of the field, at the foot of a steep slope or bluff where the soil was in very good condition, and the canes were uniformly very good over an area of perhaps an acre. The soil was deep loam in very good condition, with a clayey subsoil which gave excellent drainage.

The first stool of canes examined in this location was selected after considerable search, as being the healthiest stool of canes in the healthiest patch in the field. From the soil about the roots of this stool thirty-nine grubs, twenty-one pupae, and one adult were found, a total of sixty-one hard backs in the soil at the base of what would be called a perfectly healthy stool of ratoon canes. In this stool there were fifteen good, well-grown canes. This result is in strong contrast to the number of grubs found in what were called by the manager, very badly attacked canes. Five other healthy stools of canes were taken in this part

of the field, and these five examinations gave sixty-three grubs, seventy-six pupae, and nine adults.

Here we have the healthiest stool examined giving a total of sixty-one insects, and six other healthy stools a total of 209, or an average of about thirty-three per cane hole.

Another field, which may be called field D, was a field of 10 acres, in which ratoons are said always to be badly attacked by grubs. This field is situated on a slope, the eastern side being the higher, and in this part of the field the soil is light, with a yellow marly subsoil. Below this is a sink, which in times of heavy rain holds water. The soil here and to the west is very heavy and retentive, and in January 1920 was so full of water that the tracts left by the estate animals, mules and cattle, very quickly filled with water, which remained for two or three days before drying out. In this part of the field to the west of the sink, the canes were very bad, scarcely worth reaping, In this portion, six cane holes were dug out and the soil examined ; the number of grubs found was sixty-four, thirty-one fifty-nine, 102, twenty-one, sixty-four—a total of 341, and an average of fifty-seven per cane hole. Two cane holes in this same part of the field gave sixty-eight insects - an average of thirty-four. These two holes were chosen as being samples of very bad canes in the midst of a very bad patch.

Two cane holes were dug on the higher land to the east where the soil was light, the drainage good, and all the canes in excellent condition. These two stools of canes were selected as being very good canes in a patch of very good ratoons. From the soil about the roots of these canes seventy-one grubs and seven pupae were found, a total of seventy-eight insects from two healthy stools of canes, as compared with sixty eight from two very bad stools in the same field.

These two bad stools were of considerable interest. They grew on the edge of a field trench ; the only living roots were found in the top 5 or 6 inches of soil, but strong roots were found extending down to a depth of fully 2 feet.

The rainfall on this estate was very badly distributed in 1919, when these canes were making their growth. In the first nine months, that is to say, until nearly the end of September, the rainfall recorded was only 22 inches, and from the last few days in September until the end of the year, about 28 inches more were recorded. During the dry months the roots of these canes had penetrated deep into the soil, and had been able to maintain the canes in good condition in spite of the drought ; but with the advent of heavy rains, the sink which was some 40 or 50 yards away, and on higher ground, was filled with water for which no proper run-off was provided, and the soil of the field on the slope below was maintained in a saturated condition. The deeply penetrating roots which were developed in the dry weather were killed by the excess of moisture after the rains came, and the plants in the attempts to save themselves had been compelled to develop a few surface roots, which under the conditions existing were far from being equal to the task that was imposed on them.

On other estates in the district where these grubs occur, similar conditions were found to exist. The estate which has already been dealt with (estate A) is situated near the centre of the infested area. Near the southern limit of the grub distribution, examinations were made in several cane fields. In one field of very good plant canes, in which spots of unhealthy canes were to be seen scattered through the field, average canes gave, in one instance, twenty grubs in three cane holes, and in another, twenty-four grubs in three cane holes. At one point in this field the canes were very bad ; entire stools had died out, and there were no canes for reaping here. In this very bad spot no grubs were to be found. It was a typical root disease condition where the soil was heavy and compact, and entirely lacking in tilth. The soil was holding moisture although the land had a considerable slope.

On this same estate, in another field, second ratoons, one cane hole examined gave thirty-nine grubs, and another sixty.

On another estate several examinations were made in a field where the soil was light and the drainage good, and no grubs were found In another field on this estate where the soil was very heavy and the drainage was obviously insufficient, and a considerable patch of canes presented a typical root disease condition, sixty-seven grubs and pupae were found in one cane hole. Other examinations in this same bad patch gave no grubs

On another estate not far distant from the one last mentioned, no grubs were to be found, although a considerable number of examinations were made, including several where the canes showed the typical appearance which, in the district where grubs are numerous, would have been called the results of grub attack. The soil on this estate was, for the most part, light and easily drained, but appeared to be lacking in organic matter, and the district is one which suffers from drought. In a district to the south of the grub infested localities, and on an estate not more than 3 miles in a direct line from estate A, no grubs were found This section is separated from the grub-infested district by a range of low hills. The soil is mostly very heavy, difficult to drain, and in many fields the canes presented even a worse appearance than in those fields where the grub attacks were most severe.

There could be no doubt that in this grub-free district, the condition of the unhealthy canes was entirely due to the unfavourable soil conditions, and the presence of root disease.

These instances might be multiplied from the notes made on these soil examinations during the visit in 1920. Enough has been said, however, to show that in Antigua there is no characteristic appearance of the canes to indicate attacks by soil grubs. Perfectly healthy canes have been grown in fields heavily infested with these grubs, and the soil about the roots of such stools of canes has been found to contain grubs greatly in excess of what have been found in the soil at the roots of certain very badly diseased canes in some adjoining fields. Also there is no consistency in the figures showing the numbers of grubs found in the soil at the roots of badly diseased canes, these numbers ranging from none and very few in many instances to over

a hundred in a few cases. In the infested district the figures seem to show that generally, the heavy soils, when drainage is insufficient, contain more grubs than the lighter soils ; but even in this respect the figures are not consistent, because as shown in the account of fields C and D, heavy infestations were found in the case of healthy cane stools grown in light soils under good conditions.

That the occurrence of grubs is not associated with heavy or light soils, is shown by the results of examinations on two estates just outside the grub-infested district. On one of these estates the soil was light and easily drained and no grubs were found there ; on the other, the soil was very heavy and drainage was extremely difficult, and on this estate also no grubs were found.

The same appearance of unhealthy canes was to be seen in all parts of the island where sugar-cane was grown on heavy soils and on light soils, more frequently perhaps on the heavy soils, and this unhealthy appearance could be explained in nearly every instance by ascribing it to some other fairly obvious cause, and it could not be explained with any degree of certainty in any instance, by attributing it to the attacks of grubs.

In some instances the grubs were found in such numbers as to make it seem almost certain that they must have had an injurious effect on the canes.

In Mauritius, under the law in force there for the control of hard-back grubs, if examinations in any field indicate the presence of 20,000 grubs or more per acre, it is required that the soil of that field shall be dug up and the grubs collected and destroyed.

In the fields examined in Antigua, the numbers of grubs found indicate an infestation in many fields much more severe than that set as a standard in Mauritius For instance, in field C. already mentioned, the number of grubs found in ten cane holes in average and bad canes, gave an average of 32·5 per cane hole, and allowing 2,000 cane holes an acre, would give an infestation amounting to 65,000 per acre ; and in the same field six examinations gave an average of thirty-three per cane hole in exceptionally healthy canes showing no signs of attack ; the infestation per acre in this portion of the field would be at the rate of 66,000.

In field D, the infestation as calculated on the basis of six investigations averaged fifty-seven per cane hole, or 101,000 grubs per acre, while the healthy canes in the same field, as shown by four examinations, were infested at the rate of 69,000 per acre.

It may be of interest to consider the system on which canes are grown in Antigua at the present time.

On most estates in that island, the system of cropping includes plant canes, 1st ratoons, and second ratoons, in some fields at least ; while in rare instances there are probably still some fields of 3rd ratoons grown.

On those estates which are under contract to grow canes for the factory, there is practically nothing in the way of a system of crop rotation The fields are given good preparation for the

planting of the canes, and usually good application of coarse organic manure is made. The ratoon canes in normal times receive artificial manures, and when the ratoon series is at the end, the land is prepared for canes, and is returned to that crop in the next planting season. Indian corn, onions, and sometimes bean crops of one kind or another are grown in these fields, but only in the time between the reaping of the ratoons and the time when the young plant canes are too far advanced to allow of inter-cropping. Indian corn is often planted after the land is prepared and before the cane plants are put in, the corn ripening either just before, or just after the canes are planted ; and, if the weather conditions are favourable, Indian corn may be immediately planted again, and a second crop taken off before the canes completely cover the ground.

It would seem that this system of forcing the land must be responsible for the condition which produces the so-called root disease. The soil becomes compacted and quite unsuitable for the development of cane roots, when any unfavourable condition, such as extreme drought, or excessive rainfall is experienced. For the improvement of this condition, a crop rotation system has been recommended, providing for a full season's rest from canes after the first ratoon crop has been taken off, or in exceptional cases, after second ratoons. There can be no doubt, however, that great improvement would follow if the land could be rested from canes without bearing any ratoon crops at all.

The remedy for the root disease condition is better cultural methods, which include more frequent tillage, that is to say preparation for plant canes, and the more frequent application of coarse manures, which can only be made when the land is prepared for plant canes On heavy lands drainage requires most careful attention, and in addition, the introduction of a proper rotation crop at frequent intervals.

The following instances may be cited as showing that these purely cultural methods may be depended on to remove the condition which has long been known as root disease, and which in some places is now spoken of as grub attack.

In Antigua some six or seven years ago, certain cane fields were producing such poor canes that it became a question as to whether it would be profitable to grow sugar-cane in these fields any longer. The condition was that of a typical root disease condition, with stunted, unhealthy and rotten canes in which many of the shoots were dead. These fields were situated in the centre of the grub-infested district, but at that time the grubs were not known to occur in any considerable numbers

During the reaping season in 1920, the manager of the estate took the writer to see these fields. The canes were then being reaped ; they were extremely good, healthy canes, giving, it was said, a yield in one case of 36 tons per acre, and in the other of 40 tons per acre. No attempt had been made, in bringing these fields up to their present standard, to combat soil grubs or root disease as such ; but by attention to purely agricultural practice in the matter of manuring, frequent tillage, the use of green dressings, and attention to drainage, the root disease condition had been entirely eliminated.

In another instance, in St. Kitts, the writer was asked to examine the conditions existing on an estate in January 1911. This estate had formerly been maintained at a high standard of cultivation, but at that time many fields showed a typical root disease condition. The manager, however, attributed the condition of the canes in these fields to the attacks of the St. Kitts brown hard back, which had been discovered in the soil of the sugar-cane fields about two years previously.

At the beginning of 1920 the conditions on that estate had not improved to any great extent, but in December 1920 a very marked improvement was to be seen. This result came about by the application, during 1920, of those remedial measures already referred to - improved cultivation, the use of increased amounts of manure, and in particular, the careful selection of planting material.

In a paper on some new West Indian species of the melolonf thid genus Lachnosterna, published in the *Bulletin o, Entomological Research* for December 1920 (Vol. XI, page 189) Mr. Gilbert J. Arrow describes five new species, one of which is the brown hard back of Antigua, to which he has given the name *Lachnosterna Antiguae* The other new species are *L. Jamaicensis*, *L. Montserratensis*, which are recorded from Jamaica and Montserrat, respectively ; and *L. acinosa* and *L. dilemma*. both of which are recorded from Trinidad. In this paper it is also stated that twenty-four species of this genus were enumerated in Messrs. Leng and Mutchler's list of 1914, in addition to which four species from Porto Rico have been named by Mr. Eugene Smyth (*Jour. Dept. Agric.*, Porto Rico, 1, 1917). Two other species have been assigned to the genus Phytalus.

Arrow discusses the other generic names which have been proposed or used to apply to these beetles, such as Brahmina, Holotrichia and others, as well as the newer generic name Phyllophaga which has been adopted in recent American works on the subject ; and he concludes that so far as the American species of this genus are concerned they should all be included in the genus Lachnosterna.

Including the five described by Arrow in this paper, there are now known thirty-five species of this genus Lachnosterna from the West Indian islands, many of which Arrow concludes are probably of economic importance.

The following is a translation of Arrow's description, which is based on numerous specimens from Antigua, and there is also one record of the occurrence of the species in Dominica

Lachnosterna Antiguae, Arrow.

Testaceous red body below, with the feet and antennae yellow ; cylindrical, somewhat elongate, pruinose, not shining, thorax densely and the abdomen, in the middle, sparsely yellow-haired ; head not broad, coarsely and roughly punctate, clypeus shining, excavated, bilobed ; pronotum fairly strongly not closely punctate ; broad, with the sides strongly arcuate, scarcely crenulate, anterior angles obtuse, posterior rounded ; scutellum unequally punctate ; elytra lightly moderately closely

punctate, costa and both discoidal sutures scarcely perceptible; pygidium a little more densely punctate, feet moderately slender, fore tibiae three-toothed with claws strongly toothed in the middle; antennae nine-jointed, club three-leaved.

Male, club of antenna equal in length to foot stalk, sixth article very short laminated, tarsi of hind feet longer than the tibiae.

Female, club of antennae short, tarsi of hind feet much shorter than the tibiae.

Notes on the Life-History of L. Antiguae.

The life-history of the Antigua brown hard back has not been worked out, but the following notes may serve to give some idea of the life-cycle and habits of this pest.

The sources of information are the same as in the first part of this paper The present writer has made observations or collected specimens during brief visits, from 1911 to 1919 and during a more extended visit of about two months in January, February, and March 1920.

Dr. H. A. Tempany, when Superintendent of Agriculture for the Leeward Islands, collected specimens and made observations, 1910 to 1916, and Mr. E. S. Eldridge made periodical visits to estate A (previously referred to) on which the brown hard back was considered by the manager a pest of some importance, for the purpose of making observations. These visits, in the first instance, from May 1919 to January 1920, resulted in weekly soil examinations for the whole of that period, the sequence being broken now and then by rains preventing field work on the days chosen. During the writer's visit in 1920, he was accompanied by Mr. Eldridge, and assisted by him during the whole of that visit. Subsequently similar observations were made during March and April, and Mr. Eldridge has also contributed notes on pupation, emergence, and egg-laying, as well as on the habits of feeding of the grubs.

The hard-back beetles (adults) have been taken in Antigua in March 1916, 1919, April 1915, May 1911, 1912. During the course of the observations in 1919, which began with Mr. Eldridge's visit of May 1920, adults were found in the soil in May, June and July. From July 8, the date when seven adults were found in the soil of a field of plant canes, no more adults were found until January 9, 1920, when two beetles were dug up, still in their pupal cells; they were freshly emerged, and had not taken on the characteristic colour of the beetle as it is usually seen.

The first beetles to be taken issuing from soil were those collected on March 8, when this estate was visited after dark. The beetles were collected with the aid of an electric torch.

Dr. Tempany observed a swarm of hard-back beetles in a cane field on April 27, 1916, and Mr. Eldridge reports an abundance of beetles, the numbers apparently being equal to a swarm, but acting as individuals and not as a swarm, in

the cane fields on May 18, 1920. This was after a rainfall of 1·50 inches on the previous day.

All the beetles collected from January 29 to March 8 in this season's work, were either in the pupal cells, or at such a depth in the soil as to indicate that they had not yet left the soil, even though they may have escaped from the pupal cell. No pupae were found from the time the observations commenced in May 1919 until late in January 1920. Pupae had been previously found in March 1919. Eggs of the hard-back were found in the soil in May and July 1919. Grubs have been found in the soil during the entire year from May 1919 to May 1920, and at all times there have been full-grown larvae whenever soil examinations have been made. Very small, small, and half-grown larvae are recorded from May to September 1919, and small larvae began to be found again in May 1920.

The evidence so far obtained indicates that while grubs, apparently full-grown, are present in the soil in the infested district in Antigua at all times of the year, there is a very definite season for pupation and for the transformation of the pupa to the adult. The actual time for the adults to come forth from the soil appears to depend on the advent of rains sufficient in amount to soften the surface of the soil.

The parasite wasp, *Tiphia parallela*, has been found in Antigua. The adults are to be seen at times in some numbers, but evidences of parasitism are very few. Hard-back grubs with parasite larvae attached were found only twice : one on January 29 and one on January 30, 1920, in the course of the series of the soil examinations carried out on one estate in May 1919 to May 1920. Adults have been observed in any number on this estate only a few times during January, February and March, and Tiphia cocoons have been found in the grub-infested soil.

During the year's observations under review, nearly 4,000 grubs have been collected on this estate, and only two of the grubs have been definitely parasitized. On eleven other estates where grubs were found in the soil, 333 grubs were collected with only one instance of parasitism being found, while in one other case, a parasite larva, presumably Tiphia, was found in the soil, not attached to its host.

Two tables are given herewith, which show in concise form the results of the observations on estate A during the year 1919-20. The first, Table I has to do with the periodical visits from May 1919 to January 1920 ; while the second, Table II, records observations made during 1920, including seven night-visits for the collection of the beetles.

Table I.

WEEKLY VISITS, MAY 20, 1919 – JANUARY 2, 1920.

Date of visits.	Number of grubs.	Notes.
1919.		
May 20 ...	59	Two beetles and two eggs.
„ 27 ...	62	One beetle and five eggs.
June 4 ...	69	Three beetles.
„ 10 ...	24	
„ 17 ...	32	Skeletons of beetles.
„ 24 ...	78	Some of these grubs very small.
July 1 ...	88	One adult.
„ 8 ...	49	One adult.
„ 15 ..	37	Some of these grubs small.
„ 23 ...	138	
„ 29 ..	101	Some of these grubs small.
Aug. 5 ..	103	Grubs of various sizes.
„ 12 ...	99	Grubs large and small.
„ 19 ...	77	„ „ „ „
„ 26 ...	88	Grubs half-grown to full-grown.
Sep. 3 ..	52	
„ 10 ...	98	Grubs half-grown to full-grown.
„ 16 ...	59	Grubs small to full-grown.
„ 24 ...	77	Small grubs continue to be found, especially in ratoons.
Oct. 7 ...	48	
„ 22 ...	66	
„ 29 ...	75	
Nov. 5 ..	78	
„ 26 ...	184	
Dec. 4 ...	90	
„ 22 ...	38	
1920.		
Jan. 2 ...	33	
26 visits ...	2,002	

Table II.

VISITS DURING JANUARY, FEBRUARY, AND MARCH 1920.

Dates of visits.	Grubs.	Pupae.	Adults.	Notes.
1920.				
Jan. 14 ...	12			
„ 19 ...	341			
„ 23 ...	46	1		
„ 24 ...				
„ 27 ...	71	7		
„ 29 ...	278	23		
„ 30 ...	670	118	5	
Feb. 6 ...	122	17	2	
„ 9 ...	117	71	10	
„ 17 ...	55	4	3	
„ 18 ...	157	2	1	
„ 19 ...				
Mar. 5 ...	9	1	11	
„ 8 ...				Night.
„ 12 ...				„
„ 19 ...			9	„
„ 23 ...			2	„
„ 26 ...	5	2	24	
April 21 ...			1	Night.
„ 22 ...			1	„
„ 27 ...	40	2	44	Dead beetles in soil. Adults not in cells.
May 4 ...	15		60	Many of the beetles still in cells
„ 18 ...			293	Night. 1·50 inches rain, May 17
	1,938			May 4, one egg was found. On April 27, and May 4, small grubs began to be found, indicating that the eggs of the new generation had already begun to hatch.
16 day 7 night				
23 visits				

Eggs of the brown hard back have been found in the soil of cane fields in Antigua, and have been obtained from beetles in captivity, but no records are yet available as to the length of time spent in the egg stage by this insect, nor as to the length of time during which the female beetle is capable of laying eggs.

Trials have been made in rearing the insect from egg to adult, in confinement in Antigua, but no successful rearing has yet been reported.

The available records, based on experience with very few individuals, indicate that the insect spends some three to five days as pre-pupa, and from seventeen to twenty-five as pupa. Newly emerged adults, if exposed to light, acquired the characteristic testaceous red colour in two days.

Adults appear to remain in the pupil cell for some time, making their way out and to the surface of the ground, after a rainfall sufficient to soften the soil.

Several trials have been made to endeavour to learn whether living plant material (living roots) is necessary for the food of this insect, and in several instances the indications were that decaying cane trash was preferred to the roots. Field observations suggested the same conclusion, since under certain conditions, the grubs have been found in greater numbers where there was an abundance of decaying matter than where there was a plenty of living roots without decaying organic matter.

The only direct control measure which so far has seemed to promise any considerable reduction in the numbers of this insect in the cane fields in the infested area of Antigua, is the growing of a trap crop of maize, and collecting the grubs from the soil when the corn is pulled. Corn planted in fields known or suspected to be infested with grubs, is pulled whenever attack becomes noticeable from the condition of the corn plants. In this way, on estate A, thousands of the grubs have been collected and destroyed.

The following table gives figures showing the numbers of grubs destroyed in certain fields in 1918 and 1919.

TABLE III.

NUMBER OF GRUBS DESTROYED IN CONNEXION WITH THE GROWING OF TRAP CROPS OF INDIAN CORN ON ESTATE 'A' DURING 1918 AND 1919.

Year.	Area of field.	Number of grubs.
1918	10 acres	57,535
"	" "	7,500
"	12 "	37,000
"	14 "	25,938
"	" "	33,538
1919	16 "	25,950

It would appear that the destruction of large numbers of grubs in the soil before the planting of the canes would be of value in preventing injury to the cane crop, and in particular to the young canes.

At the present time the control exercised by the parasite, *Tiphia parallela*, on the Antigua brown hard back is negligible so far as the observations thus far made have indicated. *Tiphia parallela* is present in Antigua, and it attacks these grubs but not to any extent, and this appears to be true both in the centre of the infested area where the grubs are abundant, and on its borders where they are not present in great numbers.

In Mauritius, it was found that it was possible to establish *Tiphia parallela* on its introduction from Barbados, because of a suitable food plant for the adult Tiphias. This plant is *Cordia interrupta*, the leaves of which are provided with vesicular hairs. The adult Tiphia is not a flower visitor, but feeds normally on the sweetish secretions of aphides and related insects. The vesicular hairs of *Cordia interrupta* are said to have sweetish contents, on which Tiphias also feed.

It is suggested that the establishment of *Cordia interrupta* in the vicinity of those cane fields where the hard-back grubs occur in numbers may be of value in encouraging the spread of Tiphia in the infested area It has also been found in Mauritius that the Phytalus beetles resort to the cordia plants and feed on its leaves.

The establishment of *Cordia interrupta* near sugar-cane fields in grub-infested districts would therefore serve a double purpose. The adult Tiphias, thus provided with a suitable food plant would be attracted to the vicinity of situations in which hard-back grubs occur; the hard-back beetles could be collected from these plants and destroyed.

At the present time, in considering the measures to be adopted for the improvement of the sugar-cane crop in Antigua, the greatest importance must be attached to those agricultural practices which will improve soil conditions. The brown hard back appears to be of very secondary importance in producing the unfavourable conditions of sugar-cane often referred to as resulting from its attacks.

The establishment of plant canes is sometimes seriously interfered with during the two or three months immediately following planting. Onions, Indian corn, sweet potatoes, and yams are frequently seriously attacked by the hard-back grubs.

Planters on whose estates the hard-back grubs are present in such numbers as to be a pest, should endeavour to keep their numbers down by the use of trap crops of Indian corn, and the collecting of the grubs.

REPORT ON THE PREVALENCE OF SOME PESTS AND DISEASES IN THE WEST INDIES, DURING 1919.

(Compiled from the Reports of the Principal local Agricultural Officers.)

This is the eleventh report in this series, the latest previous one, that for the year 1918, appearing in the *West Indian Bulletin*, Vol. XVIII, Nos. 1 & 2, 1920, p. 34.

The present report covers the period January to December 1919, and has been prepared in the same way as in previous years, from information supplied by the Agricultural Officers in the several islands.

ENTOMOLOGIST'S VISITS. The Entomologist visited Grenada during December 1918 and January 1919. Reference to this visit was made in last year's report. In March, the Entomologist visited Antigua and St. Kitts-Nevis, in connexion with hard back grubs and cotton pests, and in August a visit was paid to St. Lucia, having general reference to the prevalence of insect pests.

MYCOLOGIST'S VISITS. The Mycologist spent a week in Grenada at the end of February, for the purpose of gaining further information as to the red ring disease of coco-nuts. Some inoculation experiments were started, the results of which have been recorded in the *West Indian Bulletin*, Vol. XVIII, Nos. 1 & 2, 1920, p. 73.

In accordance with an arrangement made at the conclusion of Mr. Nowell's previous visit to Trinidad, December 1918 to January 1919, a second visit was paid in September 1919 in connexion with froghopper infestations on sugar-cane. Mr. Nowell's report, embodying the conclusions reached during this visit, appeared in the *Bulletin of the Department of Agriculture, Trinidad and Tobago*, Vol. XIX, Part 2, 1920, p. 52.

Remarks on Climate.

AMOUNT AND DISTRIBUTION OF RAINFALL.

GRENADA. Rainfall at Richmond 73·09 inches, fairly well distributed.

ST. VINCENT. 109·59 inches of rain fell at the Botanic Station during the year. February and March were the two driest months, and August and November the wettest.

ST. LUCIA. The rainfall for the year ranged as follows: In the driest districts from 62·25 to 73·39 inches with 144 to 259 wet days. In the wet districts from 78·78 to 122·31 inches with 187 to 295 wet days. The distribution throughout the year was very good, August and November being the wettest months.

DOMINICA. The rainfall at the Botanic Gardens was 68·03 inches, or 3·61 inches below that of 1918. The year was remark-

able on account of the prolonged drought on the leeward coast, which extended from January to June. The rainfall at the Botanic Gardens during that period was only 15·47 inches. Reports from the inland and windward districts indicated normal conditions of weather.

MONTSERRAT. The average rainfall at twenty-three stations was 55·22 inches, or about 2 inches less than the average for the previous twenty-five years. The distribution of the rainfall was normal up to the month of July, but the drought experienced in the months of August and September had an adverse influence on cotton, the staple crop.

ANTIGUA. The rainfall on the whole was good and evenly distributed, March being the driest month, and November the wettest. A rainfall varying from 10 to 16 inches was experienced during the month.

NEVIS. The early part of the year was dry, and great difficulty was experienced in getting the crops established. The rainfall for the year was 38·22 inches.

For quarter ending March 31	...	4·71	inches.
„ „ „ June 30	...	7·18	„
„ „ „ Sept. 30	...	7·78	„
„ „ „ Dec. 31	...	18·55	„

BRITISH VIRGIN ISLANDS. The rainfall during the year was 50·36 inches.

ABNORMAL OCCURRENCES (PERIODS OF DROUGHT, WET WEATHER, WIND).

ST. VINCENT. Weather was abnormally wet during November, which caused considerable loss to the cotton crop by inducing external boll diseases.

DOMINICA. Conditions during 1919 may be accounted favourable. Torrential rains fell on the leeward coast on September 1, and again on November 29 and 30, but from an agricultural standpoint, no great harm was done on either occasion.

ANTIGUA. No definite season of drought, but heavy rains were experienced in October and November. On November 10 and 11 heavy rains fell, a precipitation of 9 and 10 inches having been measured in many places; while on November 29 a very heavy downpour occurred; between 3 a.m. and 10 a.m. 4 and 5 inches were registered, with 3·30 inches in St. John's. Very low temperature was recorded on November 11, of 59° F. at 6 a.m., and in many instances the temperature did not rise above 70° F. all day.

Lowest barometer reading for the year was 29·794 at 5 p.m. on September 2, when the centre of an incipient hurricane, evidently originating between Antigua and Montserrat, passed over the island.

There was a sharp and prolonged shock of earthquake on November 14, at about 4.20 a.m.

NEVIS. From January to June the weather was dry, and the rainfall during this period was badly distributed. The month of October was the wettest for the year, the rainfall being 8·61 inches for the month.

INFLUENCE OF WEATHER ON CROPS.

GRENADA. The weather was normal.

ST. LUCIA. The weather was exceptionally favourable for all crops, and the seasonable distribution of rainfall helped considerably towards the control of scale insects by fungus parasites.

DOMINCA. The effect of the drought experienced on the leeward coast between January and June was to delay the lime crop in this district, which in consequence, did not reach its maximum until November. Under ordinary conditions, the lime crop is at the maximum about July to August.

ANTIGUA. On the whole, the weather was very favourable for the crops, but a low rainfall in August and September, followed by heavy rains of 10 inches approximately in October, and 14 inches in November, caused a severe setback to the canes, the wet, cold soil causing root troubles.

NEVIS. On account of the irregular rainfall during the early part of the year, it was found very difficult to get the crops established, and both the cane and cotton crops were late. The heavy rains from September on were of great benefit to the cane crop, but were much against the cotton crop, as they caused boll-dropping and chilled bolls.

BRITISH VIRGIN ISLANDS. Very favourable weather conditions were experienced in the British Virgin Islands during 1919, and the prevalence of insect pests may be said to have been less severe than in any previous year.

PART I. - INSECT PESTS.

Sugar-Cane.

MOTH BORER (*Diatraea saccharalis*).

GRENADA. Present. Attack local, and in some instances severe.

ST. VINCENT. Damage done much less than in previous years

ST LUCIA. Generally distributed; no serious damage reported.

ANTIGUA. Generally present in all cane fields, especially those carrying young sprouts.

ST. KITTS. Moth borer has been observed in all districts, but there has been no definite increase in its attacks during the past year.

NEVIS. Occurred in some places to a fairly great extent. Observed throughout the island, but generally, not so severe as in the past.

BRITISH VIRGIN ISLANDS. Generally distributed.

Weevil Borer (*Sphenophorus sericeus*).

GRENADA. Not observed.

ST. LUCIA. Generally distributed, but not serious.

ANTIGUA. Generally present in all cane fields, but cannot be considered a serious source of loss.

ST. KITTS. This insect only occurs in rotten canes, and no case of any distinct damage to growing crops has been observed.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS. No record of its presence during the year.

Root Borers (*Diaprepes abbreviatus*).

GRENADA. Present.

ST. LUCIA. Present, not severe.

ANTIGUA. Not observed since 1917.

ST. KITTS. This has not been observed in St. Kitts.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS. Generally distributed in all districts.

(*D. famelicus*, var. *esuriens* [Exophthalmus esuriens]).

GRENADA. Not observed.

ANTIGUA. Adults of *Exophthalmus esuriens* were fairly common in cane fields. Not held responsible for much damage.

ST. KITTS. The beetles are found in large numbers in the heart of the canes, and on the cotton plants, but there has been little damage from the attacks of these root grubs as a general rule

NEVIS. Adults observed on hedges in the neighbourhood of cane fields, but grub not observed.

BRITISH VIRGIN ISLANDS. No record of its presence during the year.

Cane Fly (*Delphax saccharivora*).

GRENADA. Not observed.

ANTIGUA. No observations made.

ST. KITTS. Nil.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS. No record of its presence.

White Ants or Termites.

GRENADA. Present. Not observed.

ANTIGUA. Generally distributed in ratoon fields, but doing very little damage.

ST. KITTS. There has been no report of any damage from these insects, and at the Pond estate where they were formerly abundant there is a marked freedom from them.

NEVIS. Not observed as a pest of sugar-cane here.

BRITISH VIRGIN ISLANDS. No record of its presence.

HARD BACK GRUBS.

GRENADA. Not observed.

ANTIGUA. *Lachnosterna* sp. (Antigua brown hard back) were found in large numbers in the heavy fields of the central plain of this island. Undoubtedly the grubs of this pest are responsible for a certain amount of damage to young growing plants, and to ratoon sprouts ; but it is believed that the present loss attributed to this pest would be considerably lessened, if better cultivation and drainage were accorded to the fields in which the grubs were found to exist.

Ligyrus tumulosus were also found in newly manured fields, but no damage to canes has been attributed to them.

ST. KITTS. The brown hard back (*Lachnosterna patruelis*) is very common, and, where conditions are adverse, considerable damage is done, especially is this so when Marasmius attacks the cane.

NEVIS. (*Ligyrus tumulosus*) observed in fields during preparation, and in manure heaps, but not considered harmful to growing crops.

COTTON.

COTTON WORM (*Alabama argillacea*).

GRENADA. Cotton worm attacked cotton in Carriacou in August.

ST. VINCENT. Severe attack late in season on some estates in the southern part of the island.

ST. LUCIA. There was a sharp and severe attack of the cotton worm on one estate, but it was controlled by insecticides

MONTSERRAT. Attacks of this insect were mild until late in the season. Large areas, however, were denuded of growth in the month of November. At this stage of growth, on account of the uncertain prospects of securing a second picking of cotton, planters hesitate to attempt the thorough control of the pests.

ANTIGUA. Severe attacks of caterpillars were experienced throughout the island towards the close of the year, causing considerable loss to growers.

ST. KITTS. The cotton worm was prevalent towards the end of the year, but little damage was done, as insecticides were used. London purple was not found so effective as in past years.

NEVIS. The cotton worm was very severe in its attacks during the year. The insects first made their appearance as early as June, but the most severe attacks were during the month of October. The attack was perhaps the most severe on record, and a considerable amount of damage was done to the crop.

BRITISH VIRGIN ISLANDS. Very moderate attacks were recorde during the year.

BOLLWORM (*Heliothis armiger*).

CORN EAR WORM (*Laphygma frugiperda*).

GRENADA. Boll worms attacked cotton in Carriacou in August.

MONTSERRAT. Neither of these insects is recognized as a pest of cotton in Montserrat.

ANTIGUA. The boll worm was not observed during the year. The corn ear worm was not observed to attack cotton bolls during the year.

ST. KITTS. The boll worm has been observed in a few instances, but no actual damage was done.

NEVIS Boll worm not observed.
Corn worm observed in many fields of cotton, causing the loss of a large number of bolls.

COTTON STAINERS (*Dysdercus* spp.)

GRENADA. Present.

ST. VINCENT. On the whole, little damage was done by stainers. The attacks increased in severity towards the end of the season

ST. LUCIA. Cotton stainers were present, but occasioned no serious damage.

MONTSERRAT. Not so prevalent as in previous seasons, taking the island as a whole. Severe losses resulted in certain districts on the second crop of cotton, notably at O'Gara's. The proportion of stained cotton in the 1919 crop was 3·4 per cent. compared with 5 8 per cent. in the previous year

ANTIGUA. *Dysdercus andreae* appeared in large numbers late in the year. Means of control by trapping were put into practice, and, as a result, internal boll disease was not so prevalent.

ST. KITTS. Cotton stainers were conspicuous by their absence, and much less damage was done than in past years. They only appeared during the second picking about December. This appears to be due in a great measure to the campaign against the native food-plants of this insect.

NEVIS. The attack of stainers this year was later than usual and not so severe as in past years While the attack was fairly general throughout the island, on account of the attack being late, not much damage was done by this pest, and it was chiefly the second crop that was damaged.

BRITISH VIRGIN ISLANDS. Very severe attacks.

BUSH BUGS. (*Nezara viridula*, and others)

GRENADA. Present.

ST. VINCENT. Generally present. Well controlled by egg-parasites.

MONTSERRAT. These insects are invariably present in small numbers in the early part of the season, and unquestionably are responsible for a small proportion of stained cotton.

ANTIGUA. Common in all cotton fields, and are believed to be responsible for part of the stained cotton reaped, by injuring the bolls in a similar manner to stainers.

ST. KITTS. No report of any damage.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS. *Nezara viridula*, locally.

BLACK SCALE (*Saissetia nigra*).

WHITE SCALE (*Hemichionaspis minor*).

GRENADA Present.

ST. VINCENT. Present in fair numbers towards the end of the season. More common in the leeward than in the windward districts.

MONTSERRAT. Practically non-existent on the Montserrat cotton.

ANTIGUA. Both always seen on the old cotton plants, but not believed to be harmful.

ST KITTS. Only seen in a few cases, not sufficient to cause any alarm, and the plants were at once turned in.

NEVIS. Not so prevalent as in the past.

BRITISH VIRGIN ISLANDS. Black scale not recorded. White scale recorded as present.

FLOWER BUD MAGGOT (*Contarinia gossypii*).

GRENADA. Not observed.

MONTSERRAT. Not observed during the season.

ANTIGUA. Noticed on cotton late in October. Attacks increased in November, causing considerable damage to early planted cotton.

ST. KITTS. Not known in St .Kitts.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS. No record this season.

LEAF-BLISTER MITE. (*Eriophyes gossypii*).

GRENADA. Present. Not doing appreciable damage.

ST. VINCENT. Nowhere serious.

ST. LUCIA. Found wherever cotton is grown, and is carried foward from year to year.

MONTSERRAT. As the result of the Close Season Regulations in force, this pest is not now regarded as a limiting agent in the amount of the cotton crop, though the pest is invariably general in its distribution towards the close of the season.

ANTIGUA. Common in all cotton fields. The severity of this pest is on the decrease, due to the enforcement of the law regarding the destruction of old cotton plants.

ST. KITTS. This pest is scarcely looked upon with any alarm, as it only appears towards the close of the season. The close season for cotton has also done a great deal in eradicating this pest.

NEVIS. Fairly general throughout the island, in some places very severe.

BRITISH VIRGIN ISLANDS. Generally distributed, but not very severe.

OTHER INSECTS ATTACKING COTTON.

ST VINCENT. Bronze beetle was present in young cotton, but did no serious injury. The same applies to aphis.

MONTSERRAT. A severe outbreak of mealy-bug (*Dactylopius virgatus*) occurred on one estate in August 1919. This pest has been noticed in limited numbers for many years, particularly on second crops, and severe epidemics are likely to be sporadic.

ANTIGUA. Aphis present in very limited numbers in some fields of cotton, but are not held responsible for any damage.

ST. KITTS. In one instance cut worms gave much trouble by cutting off the young plants soon after germination. Poison baits and hoeing up the land gave good results.

BRITISH VIRGIN ISLANDS Aphis generally distributed early in the season.

CACAO.

THRIPS (*Heliothrips rubrocinctus*).

GRENADA. Present, locally severe. Least serious year since 1916. Estate fields suffering from thrips have received better cultural attention, whilst spraying with Bordeaux-nicotine has been fairly general.

ST. VINCENT. Generally present.

ST. LUCIA. Generally distributed, locally severe, particularly in low-lying lands.

DOMINICA. Present, but not in sufficient numbers to cause appreciable damage.

BEETLE (*Steirastoma depressum*).

GRENADA. Present chiefly on western side of the island. Collecting the insects by boys is steadily carried on.

ACROBAT ANT (*Cremastogaster brevispinosa*).

GRENADA. Generally distributed throughout the colony. The acrobat ant is generally associated with mealy-bugs. Tree surgery is being practised as a control measure, and in one instance crude oil is being used as an insecticide and preventive.

SCALE INSECTS AND MEALY-BUGS.

GRENADA. Present. *Pseudococcus citri* on cacao pods, and *P. nipae* on the back of cacao leaves. Associated with black ants, and reported to be retarding the fruiting of the trees.

ST. LUCIA. Mealy-bugs found on young pods and leaves during the drought on naturally drained hillsides

DOMINICA. Mealy-bugs are occasionally found clustered arouud the stems of young pods

BRITISH VIRGIN ISLANDS. Mealy-bugs plentiful on cacao trees and pods.

LIMES AND OTHER CITRUS.

ORANGE SNOW SCALE (*Chionaspis citri*).

ORANGE MUSSEL SCALE (*Lepidosaphes beckii*).

GREEN SCALE (*Coccus viridis*).

GRENADA. Limes in the lowlands have suffered from scale insect attacks. In Carriacou, spraying with kerosene emulsion and whale oil soap is practised the year round, chiefly for the control of snow scale. Spraying scale insects on limes is not practised in Grenada.

ST. VINCENT. General and severe.

ST. LUCIA. *Chionaspis citri*, generally present and severe in dry districts. *Coccus viridis*, generally present, not severe. *Lepidosaphes beckii*, generally distributed, fairly severe.

DOMINICA. A serious outbreak of *Orthezia insignis* on lime trees occurred in the Soufrèire district, and a minor attack of these insects was noticed on a few trees in the Lime Experiment Station.

A good representation of most other scale insects was in evidence in the Soufrière district, green scale (*Coccus viridis*), white scale (*Chionaspis citri*), and the purple scale (*Lepidosaphes beckii*) being the most numerous.

Scale insects are usually present here and there throughout the island, wherever suitable conditions occur, such as on poor cultivations, and on cultivations in the course of being established.

MONTSERRAT Lime cultivation was remarkably free from epidemics of such scale insects as the Croton bug (*Orthezia*, sp), and the green scale (*Coccus*, sp.) the scale insects usually associated with black blight under our conditions The damage resulting from the attacks of the purple scale, on the whole, appeared to be less than usual.

ANTIGUA. The following occur on all lime cultivations: *Coccus viridis*, *Chionaspis*, sp. and *Lepidosaphes beckii*.

ST KITTS. There is no lime cultivation of any extent in St. Kitts, but wherever lime trees are grown, scale insects attack them.

BRITISH VIRGIN ISLANDS. Generally to be seen on lime trees, but not severe.

Sweet Potatoes.

SCARABEE (*Cryptorhynchus batatae*).

GRENADA. Not observed.

ST. VINCENT. More prevalent in the windward than in the leeward districts. Locally severe.

ANTIGUA. Very common in lands which have been under this crop for several seasons.

ST. KITTS. This insect has been reported, but the damage done does not seem to be very grave.

NEVIS. Not very plentiful. Observed only in a few places.

BRITISH VIRGIN ISLANDS. Generally distributed.

CATERPILLARS (*Protoparce cingulata*, and others).

GRENADA. Not observed.

DOMINICA. No definite observations.

ANTIGUA. Fairly common in fields, sometimes causing entire defoliation.

ST. KITTS. No record of any attack.

NEVIS. Observed in many fields during the months of October and November.

BRITISH VIRGIN ISLANDS. Generally distributed.

RED SPIDER (*Tetranychus telarius*).

ST. VINCENT. Generally present, nowhere severe.

OTHER INSECTS ATTACKING SWEET POTATOES

GRENADA Slugs and *Nezara viridula*.

Ground Nuts.

GREEN BUG (*Edessa meditabunda*).

ST. VINCENT. Generally distributed. Locally severe.

MONTSERRAT. Cut worms (*Prodenia* sp.) attacked young ground nuts at the Experiment Station.

ST. KITTS. Ground nuts are grown to a small extent, and they appear free of any trouble.

Coco-nuts.

WEEVIL (*Rhyncophorus palmarum*).

GRENADA. Present. Observed present in all stages in trees which have succumbed to nematode attacks. Generally distributed.

WHITE FLY (*Aleyrodicus cocois*).

GRENADA. Present. One or two of these flies have been observed in the field. They do not appear to any appreciable extent, nor have injuries done by them been observed or reported.

ST. VINCENT. Generally distributed.

SCALE INSECTS (*Aspidiotus destructor*, and others).

GRENADA. Present. Generally distributed and generally severe. The seasons when rains are late cause coco-nuts to suffer very greatly from attacks. No spraying is carried out in an attempt to control this pest.

ST. VINCENT. Locally severe.

ST. LUCIA. Present where conditions of soil and weather are not very favourable to the plant.

DOMINICA. Several plants were attacked by this pest early in the year on the windward coast, and a fair amount of damage was done.

ANTIGUA. Generally present on under side of leaves. Does little damage.

NEVIS. Observed in all plantations, but chiefly on the old leaves Not apparently regarded as a serious pest.

BRITISH VIRGIN ISLANDS. Generally distributed.

INDIAN CORN.

CORN EAR WORM (*Laphygma frugiperda*).

GRENADA. Present.

ST. VINCENT. Very little damage done by this insect during the year.

ANTIGUA. Invariably present but causes very little loss.

ST. KITTS. This insect causes much trouble with the young corn, and has been observed in every district.

NEVIS. Very plentiful, and caused a great deal of damage.

BRITISH VIRGIN ISLANDS Locally severe.

BOLL WORM (*Heliothis obsoleta*).

ST. VINCENT. Noticeably less than in previous years.

BRITISH VIRGIN ISLANDS Locally severe.

HARD-BACK GRUBS.

ANTIGUA. Grubs of the Antigua brown hard-back beetle (*Lachnosterna* sp.) are responsible for considerable losses to corn crops, especially when grown between canes.

ST KITTS *Lachnosterna patruelis*, both in grub and beetle stages, has been observed.

OTHER INSECTS ATTACKING INDIAN CORN.

ST. VINCENT. Moth borer (*Diatraea saccharalis*) generally present. Not much damage done.

NEVIS. The common grasshopper did a fair amount of damage to the younger crop in some places.

ONIONS.

CATERPILLARS.

ANTIGUA. Invariably present in onion fields. Hand collecting is usually resorted to, and found to be the best method of control. *Prodenia* sp. common.

NEVIS. Did a fair amount of damage to young slips in the nursery bed.

THRIPS (*Thrips tabaci*).

ANTIGUA. Less common in fields during the year under review.

NEVIS. Occurred in nearly all the fields, but when the crop was ripening.

YAMS

SCALE INSECTS (*Aspidiotus hartii*).

GRENADA. Present. Of late, scale insects on yams have been more noticeable than formerly. Attacks, local and severe. Plants in one section, though treated in lime water prior to planting, suffered terribly from scales after being planted in the fields.

ST LUCIA. Generally present on the Lisbon and allied varieties of yams in dry districts.

ANTIGUA Invariably present, but does practically no injury.

ST. KITTS. Stored yams are attacked by this pest.

OTHER INSECTS ATTACKING YAMS.

DOMINICA. Occasionally the tubers are attacked by borers.

ST KITTS. The yams grown seem very healthy, but the cultivation is not of any extent.

GREEN DRESSINGS, BEANS, AND PEAS.

LEAF-EATING CATERPILLARS.

ANTIGUA. Crops of black-eye peas, Vilmorin's stringless bonavist, and Canavalia beans were slightly attacked.

ST KITTS. The pigeon pea worm has been very prevalent. Green dressings are not grown to any great extent.

NEVIS. Did a great deal of damage to the black-eye pea crop during the month of October.

BRITISH VIRGIN ISLANDS. Generally distributed.

BUSH BUGS (*Nezara viridula*, and others).

ST. VINCENT. *Edessa meditabunda* frequently met with in pigeon peas.

NEVIS. A great deal of damage was done by the common green bug, by sucking the young pods.

BRITISH VIRGIN ISLANDS. Generally distributed.

Plantains and Bananas.

BLACK WEEVIL BORER (*Cosmopolites sordidus*).

ST. LUCIA. Generally distributed. Serious in most places.

DOMINICA Plantains particularly are attacked by this borer, and bananas by the brown weevil borer (*Metamasius sericeus*), to a less extent.

ST. LUCIA. Present. Not serious.

LARGE BLACK HARD-BACK BORER (*Tomarus bituberculatus*)

ST. LUCIA. Generally distributed. Serious from April to June.

OTHER INSECTS ATTACKING BANANAS AND PLANTAINS.

GRENADA. Nematodes

Tannias, Dasheens, and Eddoes

LARGE BLACK HARD-BACK BORER (*Tomarus bituberculatus*).

ST. LUCIA. Generally distributed. Serious from April to June.

ANTIGUA. Lacewing bug.

General Remarks.

ST. VINCENT. Hymenopterous egg-parasites of bush bugs fairly well distributed. Lady-bird beetles well distributed. Hymenopterous parasites on cotton worm observed. Corythuca bug severe on Castor at the Experiment Station.

DOMINICA. The Palute or Slug (*Veronicella occidentalis*). This pest eats the leaves and shoots of provision crops. It is commonly distributed, and does a considerable amount of damage, especially to peasants' gardens.

ANTIGUA. Lacewing bug (*Corythuca* sp.), very common on old Lima bean vines. Mahogany trees were again attacked during the year by the mahogany twig borer. The attacks were, however, less severe than in the previous year. Adult beetles of *Mallodon maxillosum* were found in some numbers in old sandbox trees on one estate.

ST. KITTS. Grasshoppers do much damage to young canes in early stages of growth, especially in dry weather.

Natural Enemies of Injurious Insects.

PARASITIC AND PREDACEOUS INSECTS

GRENADA. Lady-bird beetles. Lady-birds are pretty generally distributed on the southern portion of St. George's parish, and the south-western portion of St David's. They are confined to lime fields suffering from scale insects, and to coco-nut groves affected with Bourbon scale.

ANTIGUA. *Tiphia parallela* was found parasitizing grubs of the Antigua brown hard back beetle on one estate. Adults of *Campsomeris dorsatus*, *Tachytes argentipes*, and Sphegidae were observed to be present in the island during the year under review.

ST. KITTS. Jack Spaniards are very common, and help in keeping down the cotton worm.

NEVIS. Chalcis, a parasite of the cotton worm, was discovered in certain parts of the island, where over 80 per cent. of the chrysalides were found to be parasitized.

The fiery ground beetle (*Calosoma calidum*) was observed feeding on cotton worms in the New Road district.

OTHER REMARKS.

NEVIS. No serious pest except the cotton worm occurred during the year. The cotton worm did great damage to the cotton crop, and the attack was considered one of the most severe experienced

The cotton stainer was prevalent during the latter part of the year, but, as the attack was late, less damage was done than would have been the case had the attack been earlier.

PART II.—DISEASES OF ECONOMIC PLANTS.

Cacao.

ROOT DISEASES (*Rosellinia* spp.).

GRENADA. Locally distributed, but no instance of severity recorded. For quite a few years treatment of fields with white lime or with copper compound has been practised.

ST. LUCIA. Serious in the Soufriére district, and in isolated patches in plantations in the other districts. Control measures are undertaken generally.

CANKER (*Phytophthora Faberi*, Maubl.).

GRENADA. Met with in some estates. Treatment by surgical means practised. Results apparently satisfactory. Local and not severe.

ST. LUCIA. Common in most plantations throughout the island Improved cultivation is keeping the disease under control in the larger plantations.

DOMINICA. Generally distributed.

BLACK ROT ON PODS (*Phytophthora Faberi*, Maubl.).

RENADA This disease, though present, is far from being as prevalent as formerly. This is attributed to the spray-

ing of trees for thrips with Bordeaux-nicotine, which has served the double purpose of an insecticide and fungicide. Not severe.

ST. LUCIA. Common, but fairly well controlled in the larger plantations.

DOMINICA. Generally distributed; occurs particularly on Criollo and Alligator cacao.

BROWN ROT OF PODS (*Diplodia Theobromae*, Pat.).

ST. LUCIA. Well distributed, but fairly well controlled in the larger plantations.

ST. VINCENT. Observed at the Experiment Station.

DOMINICA. Commonly met with, but not present to any great extent.

ST. KITTS. Not present to any great extent.

DIE-BACK AND STEM DISEASE (*Diplodia Theobromae*).

GRENADA. Present.

ST. LUCIA. Generally distributed, but not serious where improved cultivation is undertaken.

DOMINICA. Found here and there throughout the island where cacao is being grown under unsuitable conditions, or where proper attention is not given in the matter of drainage and shelter from wind.

BRITISH VIRGIN ISLANDS. Generally noticed.

OTHER DISEASES AND GENERAL REMARKS.

ST. KITTS. There is only a small cultivation of cacao, and the trees are fairly healthy.

Coco-nuts.

BUD ROT.

ST. LUCIA. Some suspected cases are under observation.

DOMINICA. Some suspected cases were observed.

NEVIS. Occurred at one plantation, causing the loss of a few trees.

RED RING DISEASE.

GRENADA. Generally distributed and locally severe. Wherever coco-nuts are grown, and have reached the ages of from five to seven years, red ring has appeared. Measures attempted to prevent its spread by isolation are practised

Tannias, Dasheens, Eddoes.

There has been no record of any disease during the years.

Indian Corn.

RUST (Red or Brown).

ANTIGUA. Occurs in all maize fields.

SMUT.

GRENADA. Present.

ST. VINCENT. Found occasionally, but not severe.

ANTIGUA Isolated cases found.

ROOT DISEASE.

ST. KITTS. This disease is very common, and is responsible for much loss in growing crops of corn.

ANTIGUA. Usually found attacking Indian corn when grown between young canes.

Imphee and Guinea Corn.

There is no record of any disease during the year.

Cotton.

SOFT ROT OF BOLLS (*Phytophthora* sp.).

ST. VINCENT. This did considerable damage to the cotton crop during the latter end of the year.

ST. KITTS. No appearance during the season.

MONTSERRAT. The comparatively dry reaping season was against the development of this tpye of disease, and no losses were recorded from its effects.

WEST INDIAN LEAF MILDEW (*Ovulariopsis Gossypii*, Wakef.).

ST. VINCENT. General; late in the season.

ST. KITTS. Hardly seen during the season.

BRITISH VIRGIN ISLANDS. Presence noted at the end of the season.

ANTIGUA. Generally appears on plants towards the close of the season.

NEVIS Fairly plentiful during the latter part of the year.

BACTERIAL BOLL DISEASE (External).

GRENADA. Present.

ST. VINCENT. Fairly common.

ST. KITTS. Not sufficient to cause damage.

BRITISH VIRGIN ISLANDS. Observed.

ANGULAR LEAF SPOT.

ST. VINCENT. General, but not serious.

ST. KITTS. Not present to any extent.

BRITISH VIRGIN ISLANDS. Observed.

NEVIS. Occurred throughout the island, but when the crop was somewhat advanced.

INTERNAL BOLL DISEASE.

GRENADA. Present.

ST. VINCENT. Not as serious as formerly.

ST. KITTS. Loss from internal boll disease was not appreciable, although the cotton stainer was present at the end of the season.

BRITISH VIRGIN ISLANDS. Generally distributed.

ANTIGUA. Not so prevalent as in the previous year, possibly due to abnormally dry weather, and to reduction of the number of cotton stainers during the year.

NEVIS. Fairly plentiful in a few places toward the latter part of the season, but by no means as prevalent as in the past.

OTHER DISEASES OF COTTON; AND GENERAL REMARKS.

ST. VINCENT. The physiological affection known as 'rust,' said to be due to lack of potash in the soil, was common.

ST. KITTS. The cotton was generally free from fungoid diseases.

GROUND NUTS.

No disease has been recorded during the year.

LIMES AND OTHER CITRUS TREES

BLACK ROOT DISEASE (*Rosellinia* spp.).

ST. LUCIA. Occurs where lime trees are used to supply vacancies caused by the same disease in cacao.

DOMINICA. Estates examined recently, show that this disease is being got under control, and that its spread to other trees can be prevented by isolating the infested trees.

UNIDENTIFIED ROOT OR COLLAR DISEASES.

GRENADA. Present.

DOMINICA. Collar rot on limes has appeared on several estates. On one estate grafted oranges were affected by a kind of bacterial infection immediately above the grafts.

BRITISH VIRGIN ISLANDS Generally to be seen in storm-damaged lime fields.

DIE-BACK.

GRENADA. Present.

ST. LUCIA. Occurs on badly drained, wet land.

DOMINICA. Noticeable here and there throughout the island, especially on trees in poor soil, or where tees are exposed to the wind.

BRITISH VIRGIN ISLANDS. To be seen at the Experiment Station.

SEEDLING DISEASES.

GRENADA. Seedlings were attacked by 'wilting' and 'damping off.'

DOMINICA. Damping off occurs every season in the seed-beds. Dusting the plants on the first signs of the disease with equal parts of sulphur and finely sifted lime is a necessary measure in the control of this disease.

OTHER DISEASES OF LIMES, AND GENERAL REMARKS

ANTIGUA. Lime cultivations in certain districts of the island are in anything but a healthy condition. Wind-breaks are

needed in wind-swept situations, and practically no attention is given to the growing of green dressing crops between the trees.

Sugar-Cane.

ROOT DISEASE. (*Marasmius Sacchari*, Wakker, and allied species).

GRENADA. With the exception of a 1-5-acre field, which had to be destroyed, no further record of this disease has been reported or recorded for 1919. Distribution local ; severity local.

ST. LUCIA. Generally distributed and serious on the Bourbon canes under ordinary cultivation.

ST. KITTS. This disease is prevalent in certain districts where sufficient attention is not paid to manuring and general cultivation ; but on well-managed estates, there is practically no loss from it.

NEVIS. Observed in a few places, but not to any great extent.

ANTIGUA. Common throughout the island. Attacks would appear to be more severe in fields carrying ratoon canes.

RIND FUNGUS. (*Melanconium Sacchari*, Massee).

ST. LUCIA. Occurs on Bourbon canes generally.

NEVIS. Observed in a few fields in the Batte Plane districts

ANTIGUA. Common throughout the island.

RED ROT DISEASE. *Colletotrichum falcatum*, Went).

ST VINCENT. This disease has been found in the island during the year.

ANTIGUA. Believed to be responsible for many failures in establishing good stands of canes.

PINE-APPLE DISEASE (*Thielaviopsis ethaceticus*).

ST. KITTS. Cane cuttings are affected, especially in dry weather.

OTHER DISEASES OF SUGAR-CANE, AND GENERAL REMARKS.

ST. KITTS. There has been no serious loss from fungoid diseases during the past season.

Sweet Potatoes.

GENERAL REMARKS.

ST. KITTS. Sweet potatoes are for the most part healthy, but little attention is paid to cultivation.

Onions.

BACTERIAL ROT.

DOMINICA. Generally noticeable in the store-room, but not to any great extent, when proper attention has been given in harvesting and storing.

ANTIGUA. Very little loss was sustained by this disease during the year under review.

Fungi Parasitic on Insects.

ON SCALE INSECTS.

GRENADA. *Cephalosporium lecanii* is fairly well distributed. This is readily observed by the diminution in number of the black blighted trees.

ST. VINCENT. Shield scale fungus specially noticed in some localities on mangoes.

ST LUCIA The four common species occurred as usual.

DOMINICA. Five species are known to exist in Dominica

ST. KITTS. None recorded, the weather conditions were too dry

ANTIGUA. Red-headed and sooty mould fungi fairly common.

ON ANY OTHER INSECTS.

GRENADA. *Sporotrichum globuliferum*—thrips fungus has not been anywhere observed during the year. One field where it was introduced has been sprayed for thrips. No trace of the fungus can be seen.

Phanerogamic Parasites.

LOVE VINE (*Cuscuta americana*)

GRENADA. Present

ST. VINCENT. Common on shrubs on neglected lands.

ST. LUCIA. Considerable attention was given to this pest during the year with satisfactory results.

DOMINICA. Present, but not common.

ST. KITTS. This pest is on the increase in villages, but does not interfere with plants of commercial value.

NEVIS. Spreading; observed on bread-and-cheese hedges neglected limes, and on wild bush along the roadsides.

ANTIGUA. Very few instances of this pest to be found in the island.

MONTSERRAT. There was a striking development of Love Vine late in 1919. The attacks of Love vine in this island are however, only temporary, and the pest is not known to damage seriously permanent cultivation.

BRITISH VIRGIN ISLANDS. Very common throughout the island of Tortola. The chief plants attacked are limes, sand-box trees, cotton, and pigeon peas.

MISTLETOE.

GRENADA. Present.

ST. LUCIA. Common on limes and cacao. Appreciable results have been attained in the control of this parasite.

DOMINICA. *Dendropemon caribœus*, the species which attacks lime trees, is abundant on some estates, and is responsible for much damage.

ANTIGUA. On native trees, loblolly, etc. at Long Island.

BRITISH VIRGIN ISLANDS. Noticed in slight quantities.

REMARKS ON ANY OTHER PLANT DISEASES.

ST. KITTS. Old Man's Beard (*Tillandsia* sp.) is very much on the increase, and attacks white cedar trees to an alarming extent.

SOIL SOURNESS—ITS MEANING AND SIGNIFICANCE.*

BY F. HARDY,

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PREFACE.

I. INTRODUCTORY.

II. TRUE SOIL ACIDITY AS A FACTOR IN SOIL SOURNESS.

(A) THE THEORY OF SOIL ACIDITY.

1. The meaning of the term Acid.
2. Intensity of acidity and total quantity of acid.
3. The acids of soils.
4. Colloidal substances in soils and their relation to soil acidity.
5. The measurement of soil acidity; lime requirements of soils.
6. Buffer action in soils.

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(B) THE RELATION OF TRUE SOIL ACIDITY TO PLANT GROWTH.

1. The effect of acidity on the growth of seedlings, and on the germination of seeds.
2. The effect of acidity on the beneficial micro-organisms in the soil.
3. The effect of acidity on plant disease organisms.

III. DEFICIENCY IN CALCIUM COMPOUNDS AS A FACTOR IN SOIL SOURNESS.

1. The rôle of calcium in plants.
2. The correlation between the reactions of plant sap and soil solution.

IV. THE TOXICITY OF ALUMINIUM, IRON AND MANGANESE AS A FACTOR IN SOIL SOURNESS.

1. The toxic effect of aluminium, iron and manganese-ions on plant growth.
2. The origin of salts of aluminium, iron and manganese in the soil solution.
3. The special case of manganese in the soil.

V. THE ABSENCE OF ADEQUATE AERATION AS A FACTOR IN SOIL SOURNESS.

1. Oxidation processes in soils and the factors controlling them.
2. The presence of protozoa in soils.
3. Methods of detecting and of estimating oxidative activity in soils.

PREFACE.

The following article has been compiled mainly with the object of presenting to agricultural officers and students of agronomy and plant ecology in the West Indies, the main facts connected with the modern conception of soil sourness. In it the writer has attempted to explain, in as simple language as possible, the theory of soil acidity, and to review recent articles on the subject that have appeared in the various periodicals received at the Head Office of the Imperial Department of Agriculture.†

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†Since this article was prepared for the press, the writer's attention has been drawn to a paper of somewhat similar scope that has appeared in the *Journal of Agricultural Science* (Vol. XI, January 1921, Studies on soil reaction, by E. A. Fisher). The reader should refer to this paper for a fuller discussion of the physico-chemical interpretation of soil acidity, and for a critical study of the so-called lime requirement methods for estimating it

I. INTRODUCTORY.

It has long been known that certain soils suffer from a defect which is known to agronomists as *sourness*, and that in the majority of cases the remedy for this defect is liming.

To give an exact scientific definition of soil sourness, however, is by no means simple, since the term implies a somewhat different meaning to different people. This fact becomes evident when text-books on agronomy are consulted. The chief impression given by the statement that a soil is sour is that it possesses an acid reaction. In the mind, soil acidity is usually associated with conditions of imperfect drainage, such as might prohibit the proper decay of plant residues, and favour the accumulation of humus acid substances. But this attendant conception is not always conveyed by the term soil sourness, since certain well-drained moorland, and waste land soils are frequently described as sour when they contain only a small amount of humus. Thus besides organic soil sourness we have mineral soil sourness.

The accumulation of acidic substances in sour soils has furnished investigators with a simple means of detecting soil sourness in the majority of cases, for soils that turn litmus paper red, are usually described as being acid or sour. There has thus arisen some confusion between the terms *soil sourness* and *soil acidity*. Acidity, it should be noticed, conveys to the chemist a restricted meaning which does not include all that is meant to the agronomist by the less definite term sourness.

A very widespread belief has established itself in the minds of practical men, that it is the presence of free acid in sour soils that is the chief, and even the only cause of their unproductiveness. Modern research has done much to prove the fallacy of this belief, and it is the main object of this article to demonstrate how this change of opinion has come about, and how far soil acidity *per se*, is a factor of importance in inhibiting plant growth.

When the factors responsible for the infertility of sour soils are analysed, it is found that, generally speaking, the main characteristic of such soils is the lack of easily soluble bases in them. The commonest form of easily soluble base in soils is some readily decomposed compound of calcium or of magnesium, and is usually a carbonate of either or both of these elements. A deficiency of easily soluble base in a soil permits acid substances to accumulate, so that in the majority of cases such deficiency is positively correlated with true soil acidity.

It is possible to conceive, however, that certain markedly sour humus soils, such as frequently occur in swampy districts, would never lose their sourness and become fertile even if the lack of easily-soluble base in them were to be rectified by the addition of large dressings of lime. Only thorough draining along with thorough liming would improve such soils, so that their sourness is perhaps not mainly due to a lack of base, but to imperfect aeration. Under conditions of water-logging, certain toxic decomposition products of plant residues apparently tend to accumulate in soils, and it is probably these toxins that are the inhibitors of plant growth in such cases rather than the less toxic organic acids that might also accumulate.

Considerations such as these indicate that it is very difficult to differentiate soil sourness from other conditions that are summated in the term infertility. It becomes evident, therefore, that some arbitrary definition of soil sourness must be adopted In this article the following definition has been chosen. and the review of the subject has been confined as far as possible within the limits of its meaning.

Soil sourness is *that state of a soil which is induced by a permanent deficiency of easily soluble base.*

The absence of easily soluble base, as has already been pointed out, allows free acids to accumulate in the soil solution. The exact nature of these soil acids will be discussed in its proper place, but it may be noticed that soil acids are either organic acids, such as might be formed in badly drained soils, or mineral acids whose formation does not necessarily depend on the absence of oxygen in the soil. A deficiency of base in a soil may allow certain salts of the metals aluminium, iron, and manganese to be liberated. These salts are in part hydrolysed by water so as to yield insoluble hydroxides and free acid. Hence a soil may become acidic because of the formation of aluminium, iron and manganese salts in it, as a result of a series of chemical changes which will be fully described later.

Sour soils as a rule, therefore, contain free acids in their soil solutions, but it does not necessarily follow from this that it is these acids that alone are responsible for the poor growth of plants in sour soils. It may be because of the mere fact that calcium is absent or lacking in sour soils that plants do not grow satisfactorily in them, for plants require calcium as an element essential to growth, and in many cases, relatively large amounts of calcium compounds are absorbed, when available, to satisfy the requirements of the metabolism of the organism.

The toxicity of aluminium salts, and to a lesser degree of iron and manganese salts, has long been known to plant physiologists. In those sour soils that owe their acid content to the hydrolysis of such salts, it may conceivably be the presence of toxic amounts of these metals in the soil solution, and not the coincident occurrence of free acid that is mainly responsible for infertility. This conception has been repeatedly brought forward in recent literature as furnishing an explanation of the unproductivity of many sour soils. Finally, soils whose sourness is due to an accumulation of organic acids, formed by the decomposition of plant residues under particular conditions, such as are imposed by bad drainage, may fail to support satisfactory plant growth simply because of the lack of proper aeration that is so necessary for the development and vigour of beneficial soil micro-organisms, and for the respiratory needs of plant roots. Furthermore, under these anaerobic conditions, toxic organic substances frequently tend to be produced. as has already been mentioned, so that the degree of oxidation, or the oxidizing power of a soil is one of the major factors concerned in its fertility.

From the foregoing preliminary discussion it becomes evident that in setting out to examine the causes of the infertility of certain soils, which, because of their general characteristics and

their acid reaction are classed as sour soils, it is necessary first to form an estimate of the possible effect which each of the individual factors might exert in its adverse influence on plant growth. In the following sections it is therefore proposed to consider each factor in turn, and to summarize the results that have been obtained in investigations into the relationships between the growth of plants and these factors, as tabulated below.

Factors Presented by Sour Soils which May Reasonably be Supposed to be Inhibitory to Plant Growth.

1. The presence in sour soils of acids; i.e. true acidity of sour soils.
2. The deficiency of sour soils in calcium compounds.
3. The presence in certain sour soils of toxic amounts of the metals aluminium, iron, and manganese.
4. The absence in certain sour soils of adequate aeration, the low oxidizing power of these soils thus permitting the accumulation of toxic organic substances which may or may not be acidic in reaction.

Whilst this list probably includes the most important factors presented by sour soils, it is not to be supposed that it exhausts all the factors which may be responsible for their unproductiveness. Doubtless future research will reveal other factors which play a part in giving sour soils their characteristic properties, and may greatly add to our limited knowledge of possible methods of correcting soil sourness in actual practice.

II. TRUE SOIL ACIDITY AS A FACTOR IN SOIL SOURNESS.

(A) The Theory of Soil Acidity.

In order to understand exactly what is meant by soil acidity as the most conspicuous characteristic of sour soils, it would be advisable first to arrive at some exact definition of the term *acid*, and to learn how acidity may be expressed.

The following three sections are therefore included to enable those who are not familiar with the modern teachings of physical chemistry to obtain some conception of certain terms which frequently occur in literature dealing with the subject of soil acidity.

1. THE MEANING OF THE TERM ACID.

The elementary definition of an acid as 'a substance containing hydrogen capable of replacement by certain metals, and when soluble, having a sour taste and possessing the power of turning blue litmus red,' although it conveys a general idea of the essential characters of an acid, yet is unsatisfactory for many reasons, and fails to explain completely certain reactions in which acids are involved. Attempts to frame a hard and fast definition of the term acid were all more

or less unsuccessful until the *electrolytic dissociation theory*, first propounded by Arrhenius in 1887, came to be generally accepted.

The electrolytic theory of dissociation is based on the assumption that chemical compounds whose solutions conduct electricity (i.e. *electrolytes*), break up or dissociate into portions known as *ions*, when they enter into solution in certain solvents. Ions may consist of single atoms or groups of atoms, and they carry definite electric charges. Certain of them, for instance, ions of hydrogen and of metals, bear positive electric charges, whereas others, for instance, acid radicles such as sulphate-ion and nitrate-ion, are negatively charged. As an example, we may take the electrolytic dissociation of common salt. When this compound is put into water, it dissolves and yields a solution which will conduct electricity. In other words, common salt is an electrolyte. According to the theory, it is assumed that during solution a large percentage of the common salt molecules dissociate or *ionize* into sodium ions, bearing positive charges, and chlorine ions, carrying charges of equal magnitude but of opposite sign to those of the sodium ions. Not all the common salt molecules dissociate in solution, however, for a small percentage remain unionized, yet dissolved.

The *degree of dissociation or ionization* is the fractional amount of a compound which is ionized. For any given compound, its value depends on certain factors of which the nature of the solvent, the degree of dilution, and the temperature are the chief. The properties of ions are entirely different from those of the free elements or molecules ; sodium ions, for example, have no resemblance to metallic sodium as we know it, a fact which is accounted for by the presence of the electric charges which the ions carry, and which completely alter their behaviour. The leading properties of dilute solutions of ionizable compounds are, according to the electrolytic dissociation theory, the properties of the ions themselves. Thus, all cupric salts in dilute solution owe their blue colour to cupric-ion.

Considering the special case of acids, it is to be noted that the particular acidic properties of all members of this class of compounds are due to the fact that they yield hydrogen-ions when dissolved in water, and the acidic properties are therefore simply *those of the hydrogen-ion itself*. We may consequently define an acid, from the standpoint of modern physical chemistry, as *a compound which dissociates when dissolved in water yielding hydrogen-ions*.

The *strength* of an acid depends upon the degree of ionization which it undergoes when dissolved. Hydrochloric acid is a strong acid because, in dilute solution about 75 per cent. of its molecules dissociate into ions. Acetic acid, on the other hand, is a weak acid, since only about $1\frac{1}{4}$ per cent. of its molecules dissociate.

2. INTENSITY OF ACIDITY AND TOTAL QUANTITY OF ACID.

We must distinguish carefully between the terms *degree* or *intensity of acidity*, and *total acid*. Intensity of acidity is defined as the *hydrogen-ion concentration of* an acid solution.

Total quantity of acid, on the other hand, is the *total amount of ionizable acid* which is present either in solution, or, if insoluble, in intimate contact with the solution.

Let us consider the case of N/10 hydrochloric acid and N/10 acetic acid. If these acid solutions be separately titrated with N/10 sodium hydroxide until they each give a pink colour with phenolphthalein, 10 c.c. of each acid will require exactly 10 c.c. of the alkali, and will therefore have apparently the same acidity. Actually, however, hydrochloric acid is about sixty times as strong an acid as acetic acid, for it is capable of ionizing to a degree sixty times that of acetic acid. During the titration of an acid with an alkali, as soon as the ionized part of the acid has been removed by the alkali, a further amount of the previously undissociated acid is ionized. This process is repeated with further additions of alkali, until the whole of the acid originally present has become dissociated, and its hydrogen-ions have united with the hydroxyl-ions of the alkali. The next trace of added alkali now reacts with the indicator to give a pink colour. Titration, therefore, only gives an index of the capacity of a solution to neutralize acids or alkalies; it does not give any information concerning the intensity of acidity, i.e the concentration of the hydrogen-ions in it.

It is necessary to adopt some method of expressing *intensity of acidity*. The following considerations suggest a simple convention which is nowadays generally accepted by physical chemists. We must note first, that water itself is slightly ionized, so that in a vessel containing pure water, there are innumerable undissociated molecules of water plus a certain small number of free hydrogen-ions and an equal number of hydroxyl-ions. The concentration of hydrogen-ion in pure water at a temperature of 25° C. is approximately 0·000,000,1 gram per litre, or 1×10^{-7}. Water may therefore be considered as being a very weak acid, and, if we use it as a standard for comparing the strengths of other acids, we may define *neutrality* as a degree of hydrogen-ion concentration equivalent to 1×10^{-7} grams of hydrogen-ion per litre. The strength of a centinormal solution of hydrochloric acid, that is, of a solution of hydrogen chloride containing 0·365 gram of the compound per litre, expressed in terms of hydrogen-ion concentration, is approximately 0·00916 gram of hydrogen-ion per litre, or $9{\cdot}16 \times 10^{-3}$.

In order to obviate the necessity of writing such unwieldy expressions as $9{\cdot}16 \times 10^{-3}$ for the hydrogen-ion concentration of an acid, it is customary to use logarithmic exponents of the expressions. These are known as *pH values*. The term pH is defined as the logarithm of the reciprocal of the hydrogen-ion concentration, i.e. $\text{pH} = \log \frac{1}{\text{H-ion concentration}}$. Thus the pH value for a centinormal solution of hydrochloric acid is $\log \frac{1}{9{\cdot}16 \times 10^{-3}} = \log \frac{10^3}{9{\cdot}16} = \log 10^3 - \log 9{\cdot}16 = 3{\cdot}00 - 0{\cdot}96 = 2{\cdot}04$. Similarly for pure water at 25°C., $\text{pH} = \log \frac{1}{1 \times 10^{-7}} = \log 10^7 = 7{\cdot}00$.

The ionic dissociation of water is usually expressed by the equation $H_2O \rightleftharpoons H^+ + OH^-$, or $H_2O \rightleftharpoons H' + OH'$, the symbol H' (or H') representing a positively charged hydrogen-ion, and the symbol OH^- (or OH') representing a negatively charged hydroxyl-ion. The equation indicates that the ionic dissociation of water proceeds to an equilibrium in which, according to the well-known laws of mass action,

$$\frac{[H'] \times [OH']}{[H_2O]} = \text{constant.}$$

(The square brackets signify the concentration in grams per litre of ions or molecules respectively). Since in the case of water, the mass of undissociated water is enormously large compared with the mass of free ions produced, it can be regarded as a constant, so that [H'] × [OH'] = a constant.

We have seen that the concentration of hydrogen-ion in water at 25°C. is 1×10^{-7} (pH = 7·0), and that when an acid is added to pure water, the hydrogen-ion concentration is increased, and that this corresponds to a decrease in the pH value. Now when *an alkali* is added to water, the alkali dissociates more or less completely into hydroxyl-ions and certain positive ions. Sodium hydroxide (caustic soda), for example, dissociates in high degree when dissolved in water in accordance with the equation†, $NaOH \rightleftharpoons Na' \pm OH'$. The addition to water of more hydroxyl-ions by the simple process of dissolving some hydroxide or other alkali which will yield hydroxyl-ions in the water, will cause a lowering of the concentration of hydrogen-ion in it, as may be inferred from the equation [H'] × [OH'] = a constant; for any increase in the concentration of hydroxyl-ion must be accompanied by a corresponding decrease in that of hydrogen-ion to maintain equilibrium. We may therefore define an alkaline solution as one in which the concentration of hydrogen-ion is *less than* that of water, i.e., is less than 1×10^{-7}. The pH value for any alkaline solution is consequently greater than 7·0.

Summarizing these results we note the following definitions :–

1. A *neutral solution* is one in which the hydrogen-ion concentration at 25° C. is 1×10^{-7} grams of hydrogen-ion per litre, or for which the pH value is 7·0.

2. An *acid solution* is one in which the hydrogen-ion concentration at 25°C. is *greater than* 1×10^{-7}, with a pH value of something *less than* 7·0.

3 An *alkaline solution* is one in which the hydrogen-ion concentration at 25° C. is less than 1×10^{-7}, with a pH value of something *greater than* 7·0.

3. THE ACIDS IN SOILS.

It is now admitted by the majority of soil chemists that

†Difficulties in regard to type have made it necessary to indicate the reversible nature of the equations in this paper by 'dagger' instead of by the usual 'arrow' signs.

certain substances capable of yielding hydrogen-ions occur in most soils. The following table will serve to indicate the nature of these substances. [79].* Soil acidity is the result of an increase of hydrogen-ion concentration in the soil solution in excess of that exhibited by pure water. Such an accumulation of hydrogen-ions is due to the dissociation of soil acids in the absence of a sufficient quantity of base, for when bases are present in excess, they cause a complete suppression of hydrogen-ions because of the fact that they yield hydroxyl-ions on dissociation, and these combine with hydrogen-ions to form non-dissociated water molecules.

SOIL CONSTITUENTS YIELDING HYDROGEN-IONS.

1. *Directly (when treated with water alone).*

A. *Inorganic.*

(a) Strong, highly ionized acids, such as hydrochloric and sulphuric acids.

(b) Weak, slightly ionized acids, especially carbonic acid, silicic acids, and alumino-silicic acids.

(c) Acid salts, such as potassium hydrogen sulphate, which may be moderately or slightly ionized and yield hydrogen-ions.

(d) Salts of weak bases with strong acids, such as aluminium chloride, which react with water (i e. are hydrolysed in solution) and thus produce a moderate concentration of hydrogen-ion derived from the liberated acid.

B. *Organic.*

(a) Strong, highly ionized acids such as citric and oxalic acids.

(b) Weak, slightly ionized acids, such as acetic acid.

(c) Acid salts of organic acids.

(d) Salts of weak bases and strong organic acids, such as aluminium citrate, which are hydrolysed as in A (d)

(e) Amino-acids, such as aspartic acid.

(f) Humic acids, which if they are definitely existent in the soil, are only slightly ionized.

2. *Indirectly (when treated with solutions of salts.*

A. Inorganic, especially colloidal †clay.

B. Organic, especially colloidal †humus.

It would appear from the above list of acidic substances likely to occur in a soil, that soil acidity is a very complex phenomenon. It is probable, however, that comparatively few of these possible sources of hydrogen-ion coexist in appreciable amounts in any one soil. For example, the natural occurrence in soils of strong acids, such as hydrochloric or sulphuric acid,

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*Reference is made by number to the bibliography tabulated as an appendix to this article.

†See the next section.

is somewhat rare. The former occasionally occurs in acid soils of salt marshes, and the latter in soils rich in sulphur compounds, as for example, those which contain the mineral pyrites. Soil acidity caused by the excessive use of ammonium sulphate as a fertilizer possibly owes its origin primarily to the liberation of sulphuric acid. Nitric acid, although a strong acid, is perhaps not often directly responsible for a markedly acid soil reaction, since it is quickly changed into nitrates in soil, and these are rapidly absorbed by plants and soil-organisms, or leached from the soil if not absorbed.

Carbonic acid is universally present in soils, in which it arises from the decomposition of organic matter. Salts of aluminium and of iron may readily be formed by the action of strong acids or solutions of other salts on certain mineral silicates present in soils. Hydrolysis of aluminium and iron salts yields strong acids, which in turn give hydrogen-ion by dissociation, as represented in the equations.

$Al\ Cl_3 + H_2O \rightleftharpoons Al\ (OH)_3 + 3\ HCl$ and $HCl \rightleftharpoons H' + Cl'$.

This subject will be more fully considered in another place.

Organic acids are, under certain conditions, undoubtedly formed in soils by the action of various micro-organisms on cellulose and other constituents of plant tissues. Nitrogenous organic matter in soil may give rise to such acids as aspartic acid. Under the conditions which occur in well cultivated soil, however, organic acids are usually rapidly oxidized, and so never accumulate to any marked extent. Only in badly drained soils, or during periods of excessive rainfall may organic acids be produced in sufficient amount to cause soil acidity. The general effect of organic material appears to be, indeed, in normal solids, to keep down acidity rather than to create it, for proteins in particular act as buffers, as will be fully explained later.

Perhaps no subject connected with the chemical composition of soils has been so extensively discussed as the question of the occurrence of the so-called humic acids in soils. Without going into the details of this controversy, it may be stated that there appears to be convincing evidence to prove that humus contains one or more substances capable, under certain specific conditions, of yielding hydrogen-ions, and which may therefore be classed as acidic. Whether or no these substances are of definite composition, and contain ionizable hydrogen chemically combined, or are of indefinite composition, colloidal* in character, and contain hydrogen-ions absorbed in variable amounts, is the chief point in dispute.

The majority of soils consist of the products of weathering of rock minerals, to which have been added a certain amount of organic matter, and other extraneous material which have become incorporated with the mineral débris during the natural process of soil formation. The most important soil-forming minerals are the felspars. During weathering, felspars are first hydrated by the action of water. Hydrated minerals, such as

*For an account of the meaning of the term ' colloidal', and the bearing of colloidal substances present in soils on the question of soil acidity, the reader is referred to the next section.

zeolites, are said to result, and free silica is liberated. Thus albite, or soda felspar, may yield natrolite, or soda zeolite, and silica, according to the equation—

$$Na_2O{\cdot}Al_2O_3{\cdot}6Si\,O_2 + 2H_2O \rightleftarrows$$
Albite.

$$Na_2O{\cdot}Al_2O_3\,3Si\,O_2{\cdot}\,2H_2O + 3Si\,O_2$$
Soda zeolite.

Some doubt has been expressed as to whether or no zeolites actually do exist in soils. Whilst their presence in soils has never been demonstrated by mineralogical examination, yet many of the chemical properties possessed by soils may be simply and satisfactorily explained by assuming that they constitute the more reactive portion of the clay fraction of soils. (See 64.)

After the first stage of hydration, further changes probably occur rather rapidly, and result in the formation of other hydrated silicates of which kaolinite ($Al_2O_3\,2Si\,O_2{\cdot}2H_2O$) is a common example. Probably water containing carbonic acid in solution is an active agent in the later stages of weathering, removing bases such as sodium and calcium oxides from zeolites in the form of carbonates and bi-carbonates. It is possible also, that the free silica which is liberated during many of the reactions mentioned, becomes hydrated into one or more of the various weak silicic acids.

The end products of the weathering of minerals of the felspar group, whatever the intermediate stages may be, are thus seen to consist in general of alumino-silicic acids, such as kaolinite, together with various less complex silicic acids. When kaolinite forms the most conspicuous product, the weathering process is termed *kaolinization* and in temperate climates this is the chief type of decomposition which affects the felspar minerals in rocks. Under certain conditions rock decay may, however, be even more profound. In the tropics, for example, a process known as *lateritization* frequently affects rocks rich in felspars and in iron-containing minerals. The end products of lateritization consist chiefly of various hydroxides of aluminium, such as gibbsite ($Al_2O_3.\,3H_2O$), bauxite ($Al_2O_3,\,2H_2O$), and diaspore ($Al_2O_3H_2O$), derived chiefly from felspars, together with ferric hydroxide. The presence of this latter compound usually gives to the clayey residium (laterite) a bright red colour.

Alumino-silicic acids, for example, kaolinite, and silicic acids, are more or less insoluble in water. The small proportion which dissolves, however is dissociated to some extent, and yields hydrogen-ions to a small degree of concentration. In mineral soils, therefore, there exists a large reserve of slowly reactive or potential acids, which, by reason of their limited solubility and their low degree of ionization, may impress an appreciable intensity of acidity upon the soil solution.

There occur also in soils certain minerals which may not be hydrated so as to be capable of yielding hydrogen-ions directly, but which may react with solutions of neutral salts, such as might be liberated during certain chemical changes occurring in soils, or might be added as fertilizers, so as to liberate hydrogen-ions. Thus, when potassium chloride is added in solution to a soil, the solution becomes more or less strongly acid. Although this may not be the result of a single process, yet it may in part

be accounted for, by assuming that compounds such as aluminium and iron silicates exist in the soil, and that these react with potassium chloride to form potassium silicate, and aluminium and iron chlorides. The last-named salts, as has already been stated, are hydrolysed in the presence of water, yielding hydrochloric acid, which is the direct source of the hydrogen-ions that are liberated.

4. COLLOIDAL SUBSTANCES IN SOILS AND THEIR RELATION TO SOIL ACIDITY.

It has been stated in the last section that many of the facts connected with the chemical properties of soils, and in particular those bearing on the question of soil acidity, may be explained by reference to the so-called *colloids* in soils. It would be well, therefore, to consider the nature and behaviour of soil colloids in some detail.

The term colloid does not refer to any particular substance or group of substances, but is used rather to describe a state in which any form of matter may occur. Recent research has indicated that all substances can probably be brought into the colloidal state, provided that suitable means are found for causing their dispersion.

Broadly speaking, the chief characteristic which distinguishes substances in the colloidal state, lies in the relative size of their particles. Whereas true molecules have an average diameter of about 2×10^{-8} cm., the size of colloidal particles varies between $1 + 10^{-3}$ and 1×10^{-6} cm. Substances which are in colloidal dispersion in water are neither ionized nor properly dissolved so as to give truly homogeneous systems, but the molecules are aggregated into masses which are great compared with molecular magnitudes, but which are not sufficiently heavy to settle. Colloidal dispersions are therefore heterogeneous, and contain more than one phase. Consequent on the large surface area of contact between liquids containing colloidal particles and the particles themselves, the surface energy of colloidal substances is relatively very great. As a direct effect of this, colloidal systems exhibit a phenomenon known as *adsorption*, and this is perhaps the most characteristic manifestation of the colloidal state. It is due to this property that colloidal particles are able to assimilate and hold at their surfaces, and with great tenacity other colloidal particles, molecules or ions. Thus charcoal, in a sufficiently fine degree of subdivision, can adsorb great quantities of various gases, or, when suspended in a liquid, can remove various substances from solution.

Adsorbtion effects, and indeed the properties of colloidal systems in general, are somewhat modified by electrical forces which act upon them. For example, when a colloidal particle adsorbs an ion or ions, the electric charges on the latter are supposed in certain cases to be given up to the particle, which thereby attains the power to repel a similarly charged particle. It is frequently by reason of the possession of electrical charges by colloidal particles which hold adsorbed ions on their surfaces, that their solutions are rendered stable. If the particles, by adsorbing other ions of opposite charge, have their charges

neutralized, the stability of the system is destroyed, and aggregation tends to proceed,

Different substances in the colloidal state exhibit different specific properties, especially as regards the adsorption of molecules or ions. Thus one colloidal substances may be able to adsorb molecules or ions of a particular kind, but not others. To this property is due to the power of *selective absorption* exhibited by certain colloidal substances.

Without going more deeply into the numerous other aspects and facts* connected with the subject of colloidal science, we may now proceed to consider the especial bearing of the subject on soils. It is not intended to discuss the rôle which substances in the colloidal state play in physico-chemical phenomena, such as the complex water-relations of soils, but to confine our attention chiefly to the question of soil-acidity.

The colloidal substances present in soils are either of organic or of mineral composition. The former occur in the humus component, and the latter chiefly in the finer mechanical fractions, which may be collectively referred to as clay. The mineral substances that are most usually found occurring in the colloidal state in soils are the products of hydrolysis of rock-forming minerals, i.e. hydrated silicates, such as kaolinite, etc., hydroxides, such as ferric and aluminium hydroxides, and hydrated silica, (or silicic acids).

It is not known exactly how these colloidal substances are arranged in soils, but there is evidence to show that they probably form a coating round the non-colloidal particles, or that they exist as a mesh-work enclosing these particles.

The capacity of the colloidal substances to adsorb water to various degrees of hydration accounts for most of the important physical characteristics of soils. As regards the special colloidal properties which, along with those already mentioned, have been indicated as furnishing a satisfactory explanation of many of the properties of soils, the following may be noted. It must be observed, however, that certain of the statements made are open to criticism, and that the reactions which they are held to explain can in many cases be equally well, or even more convincingly, elucidated by purely chemical reasoning, as will be briefly shown.

1. The more finely divided particles of soils, when dispersed in water are stated to be electro-negatively charged†. This is explained by assuming that on hydrolysis, certain potassium-bearing silicates present in it, liberate minute quantities of potassium hydroxide, and the loss of positively charged potassium-ions by the silicate particles, leaves the latter in possession of a negative charge. Since such particles possess negative charges, they are aggregated by positively charged

* For further information on the physics and chemistry of the colloida state, the reader is referred to the books and articles mentioned in the bibli ography (nos. 33, 53, 50, 59).

† See, however, the recent work of Comber (14 a) whose experiments indicate some differences between the colloidal state of the true clay fraction of soils and the finer silt fractions.

ions, such as those of hydrogen and of metals, so that solutions of acids and of salts are effective agents in bringing about the flocculation of the finely divided particles. The process is reversible, for the removal of the flocculating agent causes in general, immediate deflocculation.

2. Humus and colloidal soil-clay possess the power of adsorbing certain substances from their solutions. The substances adsorbed may be—

(a) *Ions of metals*, such as potassium-ions, which it is assumed can be withdrawn from solutions of neutral metallic salts independently of the equivalent and oppositely charged ions simultaneously liberated by the dissociation of the salt. Two well-known facts in this connexion require further attention.

(i) When neutral salts are added to colloidal clay dispersed in water, the liquid becomes acidic in reaction, showing that the hydrogen-ion concentration has been augumented.

The supporters of the colloidal theories of soil acidity* explain this result [8, 9, 31, 54], by assuming that the salt is first hydrolysed, and yields a hydroxide plus an acid. The former is then adsorbed *as a whole* by the colloidal clay particles, and the solution is thereby left with an acid reaction. It is difficult to understand the mechanism by which the metallic hydroxide is caused to unite with the colloidal material. Further, it would appear that, if clay can bring about such a liberation of hydrogen-ions in solutions of neutral salts, then any sort of finely divided material should be capable of producing the same result, and it should be possible to obtain varying degrees of acidity, simply by increasing or decreasing the quantity and size of the dispersed colloidal particles. No convincing data have yet been brought forward to support this generalized argument, so that the colloidal explanation is somewhat discountenanced.

The result can be equally well explained on purely chemical grounds, for we may reasonably assume that the metallic hydroxide formed by the hydrolysis of the added neutral salt actually combines with some mineral constituent of the clay instead of being adsorbed by the clay.

When we consider the phenomenon in connexion with *soil* (which contains colloidal clay), we have the additional possibility that, provided easily neutralizable bases such as calcium carbonate are absent, the development of acidity by the addition of solutions of neutral salts to certain soils can easily be accounted for, on the assumption that an exchange of bases between the salt and certain insoluble aluminium compounds of the soil takes place. The soluble aluminium salt thus produced is hydrolysed, and yields hydrogen ions in a way already explained.

(ii) The second fact, although not directly connected with the question of soil acidity, is worthy of passing mention, because of its great importance in relation to the

* For a historical account of the different theories which have been formulated to explain soil acidity, the reader is referred to 'Soil Conditions and Plant Growth.' E. J. Russell, 4th Edition, 1920. *Longmans Green & Co.*, (64).

chemical properties of soils. It is the exchange of bases that goes on when solutions of neutral salts are added to certain soils. Thus, when potassic fertilizers are added to neutral or alkaline soils, the potassium is retained, and a corresponding amount of some other base, usually calcium or sodium, is liberated, and may appear in the drainage water.

This result is explained in terms of the colloidal properties of soils by assuming, as before, that hydrolysis of the salt first occurs ; that this is followed by the adsorption of the hydroxide thus produced, but that the acid simultaneously liberated, now reacts with certain bases in the soil to form soluble salts which subsequently appear in the drainage water. In this way the presence of easily decomposed bases, such as calcium carbonate, in soils, accounts for the fact that these soils maintain a neutral or alkaline reaction, even when heavily manured with fertilizer salts, such as potassium or ammonium sulphate.

As before, this type of reaction can equally well be explained without postulating a colloidal adsorption process. It has also received a satisfactory explanation for those who hold that zeolites occur in soils by the classical researches of Way, who proved that double silicates of the zeolite type can readily exchange their bases for other bases contained in neutral salts brought into contact with them, eg.,

$$Na_2O{\cdot}Al_2O_3{\cdot}3SiO_2{\cdot}2H_2O + K_2SO_4 \rightleftharpoons$$

Soda zeolite

$$K_2O.Al_2O_3{\cdot}3SiO_2{\cdot}2H_2O + Na_2SO_4$$

Potash zeolite.

It appears from the above discussion that the reactions which go on when solutions of neutral salts are added to soils are of a very complex nature, involving various physico-chemical changes, and as yet no definite conclusions can be drawn as to the exact mechanism which accounts for all the known facts.

(b) *Hydrogen-ions* may possibly in certain cases be retained in an adsorbed condition by the colloidal particles in soils. In this condition they are said to be replaceable by metallic ions introduced into the soil by the addition of neutral solutions of salts, and certain authorities consider this to be the most important source of indirect acidity as induced by the addition of salts to soils. [79].

(c) *Hydroxyl-ions*. Sharp and Hoagland [69] have shown that hydroxyl-ions are removed by certain soils from added solutions of metallic hydroxides, such as those of potassium, sodium, barium and calcium. The experimental results indicate that selective adsorption occurs, for apparently a relatively greater amount of hydroxyl-ion is removed by soils from the two last-named hydroxides than from the first two. These results are interpreted as being due to the simultaneous removal of both positive and negative ions from the hydroxide solutions. They may be explained either as colloidal phenomena dependent on true adsorption, or as a chemical reaction in which a simple combination

between the hydroxide as a whole, and some of the mineral constituents of the soil takes place. The experimental facts have an obvious bearing on the question of the liming of soils to reduce acidity, and on the reliability of lime requirement methods for estimating soil acidity.

(d) *Molecules* of certain substances are apparently adsorbed by colloidal particles of soils under certain conditions. The removal of dye-stuffs from their solutions has been suggested as a means of determining the quantity of colloidal matter in soils. It is difficult to discriminate in all cases between the adsorption of whole molecules and the simultaneous adsorption of ions produced by their dissociation. The subject need not be further discussed, except to point out that selective adsorption is exhibited by the colloidal substances in soils towards the molecules of specific compounds.

5. THE MEASUREMENT OF SOIL ACIDITY: LIME REQUIREMENTS OF SOILS.

The following tabular arrangement [79] includes the chief methods that have been suggested for the estimation of soil acidity.

(a) *Methods of estimating soil acidity.*

I. A neutral salt solution is added to the soil.

The following salts amongst others have been used. Sodium chloride (Hopkins, 1903); calcium acetate (C. H. Jones, 1913); potassium acetate (Oscar Loew, 1913); potassium chloride (Daikahura, 1914).

II. Pure water is added to the soil.

(A) The mixture is titrated with *lime water* (Veitch, 1904. Bouyoucos, 1916), or a solution of *calcium bicarbonate* (Hutchinson and McLennan, 1914), using either an indicator or observation of the freezing point to determine the end point. This gives the amount of lime needed to neutralize the acid originally present in the soil, plus that produced by the indirect action of the calcium compound added, as well as the amount of lime required to satisfy the adsorptive power of the soil colloidal substances for calcium-ion under the given conditions. In this sense they are therefore *lime requirement* methods.

(B) The mixture of soil and water is filtered, and the acid in the filtrate estimated by titration with standard alkali. This determination gives the *total quantity* of acid extracted from the soil by the water treatment.

(C) The *hydrogen-ion concentration* of the mixture of soil and water, or of the centrifuged or filtered extract is determined.—

(a) By catalysis of an ester such as ethyl acetate (Conner, 1916).

(b) By catalysis of sucrose (Rice and Osugi, 1918)

(c) By measurement of the electric potential due to hydrogen-ion by using the potentiometer (Gillespie, 1916).

By observations of colour changes of indicators whose relations to hydrogen-ion concentration are known (Gillispie 1916).

(b) *Notes on the methods used for estimating soil acidity.*

1. The methods outlined under heading I in the foregoing table are clearly not methods of determining the acidity originally present in a soil, since the results given by them are composite in that they represent both the acid originally present, and a usually greater quantity produced by the treatment with the salt solution. Actual trial has shown that the results obtained vary with the kind of salt used, and with the conditions of the experiment [3]. In certain cases neutral or slightly alkaline soils may develop considerable acidity, when treated with a salt solution [6 9] as has been explained in previous sections. Hence the methods are of little value when employed in investigations into the effect of soil acidity on plant growth.

2. The methods outlined under the heading IIA include the most commonly used *lime requirement* methods. They undoubtedly give a correct indication of the amount of lime needed to bring a soil to the degree of alkalinity shown by the indicator used, and if the freezing point method of determining the end point is employed (Bouyoucos, [5]), it may be possible to recognize the point at which the soil acids are just neutralized, as well as that at which lime ceases to be taken up by the soil. In this way the latter method is perhaps capable of yielding results representing both total quantity of acid and lime-requirement (see summary of Bouyoucos' results,[7 8] p. 337).

3. The method outlined in IIB enables one to determine the *total quantity* of acid in a soil in the most direct and simple way. The indicator used must, however, show the correct point of neutralization as defined upon physico-chemical grounds (i.e pH = 7·0). Neither methyl orange (range pH 3·1 to 4·4) nor phenolphthalein (range pH 8·3 to 10·0) can be used. Bromthymol blue (range pH 6·0 to 7·8) would give the most satisfactory results.

4. Methods based on the estimation of the hydrogen-ion concentration of the soil extract (IIC) are of the most value in researches into the relation between soil acidity and plant growth, for it is not the *total quantity* of acid which is locked up, as it were, in the difficultly soluble alumino-silicic acids, the humus and the other acid-yielding constituents of soils, that is of importance in regulating the processes that go on in soils, but the *intensity of acidity* of the soil-solution. Recognition of this fact has given prominence to the methods of estimating soil acidity last mentioned, and these methods have largely replaced the older lime-requirement methods in researches in soil science.

(C) *Methods of measuring the hydrogen-ion concentration of soils.*

Of the four methods indicated in the table (namely IIC, a, b, c and d), the last two only are in general use in soil researches. They may be referred to as the hydrogen electrode method and the colorimetric method, respectively. The former gives more accurate results than the latter, but it is more difficult to manipulate, and necessitates the use of costly apparatus It forms the basis, however, of all accurate determinations of hydrogen-ion concentration, not only in soil science, but also in physiology and bacteriology.

It is not intended here to give a detailed account of the hydrogen electrode method, as this would necessitate too deep an incursion into the fundamental facts of physical chemistry. The reader is referred to a recent book by Dr. W. Mansfield Clark [11] for a full discussion of the theoretical and practical aspects of this subject.

The colorimetric method will be briefly described, however, for it is the method which is universally used in rapid soil surveys as carried out in modern investigations.

The colorimetric method of determining hydrogen-ion concentration is based upon the fact, that there exists for each of certain complex organic compounds called indicators, a characteristic zone of hydrogen-ion concentration within which its colour changes take place. Phenolphthalein, for instance, is colourless in solutions of hydrogen-ion concentration greater than that represented by a pH value of 8·3. If the solution is slightly more alkaline (i.e. its pH value is numerically greater than 8·3), a pink colour appears and gradually becomes more intense with increasing alkalinity, until the indicator appears to give its full colour at about pH = 10. Methyl orange, which is yellow in alkaline, neutral and slightly acid solutions, exhibits its intermediate colours between pH = 3·1 and pH = 4·4. These two well-known indicators are not altogether suitable for colorimetric work however, either because the colour change is not sufficiently sharply defined, or because the pH range is too small.

Several new and very brilliant indicators have recently been prepared and placed on the market. The pH range of each has been accurately determined by the use of carefully made solutions whose exact pH values were checked by the hydrogen electrode. [12]. The set of seven indicators described below, which together cover a pH range of 3 to 10, are generally used in the examination of soils. A special technique has been elaborated, and this enables the soil chemist to estimate with a sufficient degree of accuracy, and in the minimum of time, the intensity of acidity exhibited by any given soil sample. The technique is fully described by its inventor in a recent paper [26] to which reference must be made for full details A short abstract is given below in order to indicate the principle of the method.

It is unnecessary here fully to discuss the theory of indicators, since the colorimetric method, after all, is simply a comparative method based on absolute measurements of hydrogen-ion concentration with the hydrogen electrode; it therefore entails no knowledge of the nature or seat of the colour changes of the indicators employed. The reader is

referred to Prideaux[58] for an exhaustive discussion of the theory of indicators.

The following brief review will serve as an introduction to the description of the actual colorimetric method as applied to soils. Let us assume that indicators are acids or bases whose undissociated molecules have a different colour from that of their dissociated products. For example, let us consider phenol red to be an acid of type HA, and that the undissociated molecules HA, are yellow in colour, whilst its acid radicle-ions, A, are red. When phenol red is dissolved in a certain volume of pure water at ordinary temperature, it will dissociate according to the equation $HA \rightleftarrows H' + A'$, and equilibrium will be attained between the undissociated molecules and the ions liberated, so that $\frac{[H'] \times [A']}{[HA]} =$ a constant.

(The square brackets signify the concentration in grams per litre of the ions or molecules). The constant is known as the *dissociation constant* of the substance at the specified temperature and for the degree of dilution of the solution.

There will therefore exist, in the case of a solution of phenol red, a certain number of yellow-coloured molecules of the undissociated compound, and a certain number of acid-radicle ions (A′) of a red colour, together with an equal number of colourless hydrogen ions (H). The resulting colour of the solution will lie somewhere between yellow and red, and its exact shade will depend on the relative number of HA and A′ present.

Suppose now we increase the concentration of hydrogen-ion, by adding a few drops of some acid. The result of this will be to suppress the dissociation of the indicator, and thus to increase the number of yellow-coloured undissociated molecules. Hence the solution will assume a more yellow shade of colour. For every intermediate shade between red and yellow there will therefore be a corresponding hydrogen-ion concentration or pH value, and if we possess previous knowledge of the correlation between pH value and shade of colour, we shall be able to estimate the hydrogen-ion concentration in any given solution, provided that the range of the indicator used includes the pH value of that solution.

The simplest way of standardizing the shades of colour given by an indicator, is to employ a colour chart in which various shades of colour are reproduced with the corresponding pH value stated for each. Such a chart is published for the seven indicators usually employed in colorimetric work, at page 40 of Clark's book already mentioned[11]. Separate copies can be obtained of this colour chart. By its use a rough estimation of the hydrogen-ion concentration of a soil solution can be made, the degree of accuracy being within about 0·1 of the correct pH value. Quite recently, the La Motte Chemical Products Company, of Baltimore, have advertised an inexpensive set of seven indicators, made up into solutions of convenient strength, and contained in tubes fitting into a small box that can be taken into the field. Instructions are provided showing how approximate pH determinations can be made on the spot.

The method of Gillespie,[26] now to be described, gives results of a greater degree of accuracy than that in which a colour chart is used. The colour standards in Gillespie's method are obtained without the use of standardized solutions, in the following way. Two parallel rows of nine narrow uniform test tubes are arranged in a rack. Into each, 10 c.c. of water are placed. The indicator solution to be used is then added in drops to each tube, the number of drops varying uniformly from 1 to 9 in the first row, and 9 to 1 in the second, as indicated in the diagram. The full acid colour is then developed in the indicator solutions in the first row of tubes, by adding a small quantity of acid to each, and the full alkaline colour is similarly developed in the second row, by means of dilute alkali. If any adjacent pair of tubes, one from each row, is taken and viewed by light transmitted through both tubes, the shade of colour observed will depend on the drop ratio of the indicator present. For each drop ratio, and for each of seven indicators, the corresponding pH value has been determined, and the results drawn up in a table which is reproduced at page 126 of Gillespie's paper above mentioned.

	Number of drops of indicator in each tube.								
Full alkaline colour	1	2	3	4	5	6	7	8	9
Full acid colour ...	9	8	7	6	5	4	3	2	1
Drop ratio	1:9	2:8	3:7	4:6	5:5	6:4	7:3	8:2	91
Colour of paired tubes	yellow	yellow green	yellow green		green	blue	blue-green	green	blue
Brom-thymol blue pH value corresponding to the drop ratios when *brom-thymol blue* is used	6·15	6·5	6·7	6·9	7·1	7·3	7·5	7·7	8·05

The names and pH ranges of the seven indicators most commonly used are as follows :—

Name.	Acid colour.	Alkaline colour.	pH range.
1. Brom-phenol blue ...	yellow	purple-blue	3·0 to 4·6
2. Methyl red	red	yellow	4·4 to 6·0
3. Brom-cresol purple	buff	purple	5·4 to 7·0
4. Brom-thymol blue	yellow	blue	6·0 to 7·8
5. Phenol red	yellow	red	6·8 to 8·4
6. Cresol red	yellow	purple-red	7·2 to 8·8
7. Thymol blue ...	buff	deep blue	8·2 to 9·8

In soil work, 15 grams of the soil sample are mixed in a flask with 30 c.c. of pure water whose reaction as ascertained in a previous trial is neutral (pH = 7·0). The mixture is shaken for some time and then allowed to stand, preferably overnight. It is then centrifuged or filtered,* using the filter-pump if necessary. 10 c.c. of the clear extract are placed in a tube of the same size as those used for the colour standards, and 10 drops of the indicator solution are added. The colour developed is now compared with various pairs of tubes which form the colour standards, the tubes being held in a comparator. When the correct match has been obtained, reference is made to the table of drop ratios which gives the corresponding pH values, and thus the pH value of the soil extract is determined. The results have been found not to differ much from those obtained with the soil solution itself, as expressed from soil by the use of powerful compressors or oil pumps, [28], [57], [69].

BUFFER ACTION IN SOILS.

In order to understand what is meant by the term *buffer*, it would be advisable to consider first a simple example. Suppose a few drops of hydrochloric acid are added to a solution of sodium acetate. Both of these compounds are highly ionized in solution, but when mixed, opportunity is given for the formation, by their interaction, of two other compounds, namely sodium chloride and acetic acid, the former of which is highly ionzied, but the latter very feebly so. Hence in the mixture, the hydrogen-ions and the acetate-ions, produced by the dissociation of the hydrochloric acid and the sodium acetate, respectively, will unite almost completely to form acetic acid, and as a consequence the hydrogen-ions will very nearly disappear.

The reactions may be expressed thus :—

$$HCl \rightleftarrows H^{\cdot} + Cl'$$

$$CH_3COONa \rightleftarrows Na^{\cdot} + CH_3{\cdot}COO'$$

$$H^{\cdot} + CH_3{\cdot}COO' \rightleftarrows CH_3{\cdot}COOH \text{ (feebly ionized).}$$

The effect of sodium acetate on the ionization of hydrochloric acid is therefore to bring about a considerable reduction in its hydrogen-ion concentration, and for this reason sodium acetate is spoken of as a *buffer*.

There are many compounds or mixtures of compounds known which can act as buffers in a similar way. Their presence in such liquids as plant-sap, blood and sea-water confer on these liquids the important property of being able to resist change in reaction by virtue of their ability to soak up, as it were, excess of hydrogen-ions which may in some way or other gain access to the liquids.

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* Centrifuging is preferable to filtration because the use of filter-paper may produce an alteration in pH value by the paper adsorbing certain ions from the soil extract.

Furthermore, certain subtances are capable of functioning as buffers both against change in acidity and change in alkalinity; that is they are able to remove hydroxyl-ions as well as hydrogen-ions when these occur in excess in a solution. They are themselves so constituted that they can function both as bases and as acids depending upon external conditions, which in some way decide the kind of ionization that their molecules undergo. Examples of such substances are the simple amino-acids and the proteins. Water itself, from what has been stated about its dissociation, is also an example. They are called *amphoteric substances* or *ampholytes*, and their presence in liquids, such as those mentioned above, is of great physiological importance in that they regulate the reaction of these liquids by maintaining a constant hydrogen-ion concentration by reason of of their buffer properties.

Recently, convincing evidence has accumulated which indicates that soil solutions contain certain compounds that are able to function as buffers. The explanation by Henderson in 1909* of the mechanism of the buffer action in blood as being chiefly due to the presence of carbonates and phosphates in solution, naturally points to these compounds as the probable seat of buffer action in the soil solution. Examples of soils containing appreciable amounts of carbonate and yet possessing both considerable lime requirements, as determined by certain conventional methods, and giving an acid reaction with indicators, have frequently come to the notice of soil investigators. This apparent anomaly in connexion with West Indian soils has been commented upon by Watts [57]. An explanation of the phenomenon would perhaps therefore be welcomed.

(a) *The bicarbonate buffer system in soils.*

Calcium carbonate ($CaCO_3$) is almost insoluble in pure water, the extent of its solubility being of the order of 1 part in 100,000 at ordinary temperatures[58]. In the soil, and indeed under any other conditions in which the compound occurs in nature, calcium carbonate is exposed to the action of carbon dioxide, for both the sub-aerial and the soil-atmosphere contain the gas in varying proportions. The soil solution in contact with carbon dioxide dissolves a certain amount of the gas until a state of equilibrium is reached between the dissolved compound and that which is still in the free state in the gaseous environment. The concentration of the saturated solution is proportional to the pressure of the carbon dioxide in the environment, and thus depends on the percentage amount of the gas in the soil atmosphere.

In solution, carbon dioxide reacts in part with water to form carbonic acid which is feebly ionized into hydrogen-ions and bicarbonate-ions (HCO_3'). The following equations illustrate the relationships between the different molecules and ions in the system carbon dioxide and water :—

$$CO_2 \text{ (gas)} \rightleftarrows CO_2 \text{ (dissolved)} + H_2O \rightleftarrows H_2CO_3 \rightleftarrows H' + HCO_3'$$

*For a clear account of buffer action as exhibited by the fluids of the animal body, the reader is referred to 'Principles of General Physiology,' by W. M. Bayliss, London ; *Longmans Green*, 1920, 2nd Edition, 25*s*.

When calcium carbonate is in contact with water containing carbonic acid, the small amount of carbonate which first of all dissolves in the pure water is partly ionized into calcium-ions and carbonate-ions (CO_3^{11}). The calcium ions combine with the HCO_3-ions produced by the dissociation of the carbonic acid in the solution, and calcium bicarbonate molecules ($Ca(HCO_3)_2$) are formed. Similarly, the carbonate-ions combine with the hydrogen-ions of the acid to produce more HCO_3-ions which also enter into the formation of more bicarbonate. The equations which represent these various reactions are :—

(i) $Ca\,CO_3 \rightleftarrows Ca^{\cdot\cdot} + CO_3''$.

(ii) $H_2\,CO_3 \rightleftarrows 2H^{\cdot} + HCO_3'$

(iii) $CO_3'' + H^{\cdot} \rightleftarrows HCO_3'$

(iv) $Ca^{\cdot\cdot} + 2\,HCO_3' \rightleftarrows Ca(HCO_3)_2$ (unionized).

The ultimate result of the exposure of calcium carbonate in contact with the soil solution to the action of carbon dioxide contained in the gaseous environment is thus seen to be the formation of soluble calcium bicarbonate through a series of closely interrelated reactions which are controlled each by its special ionic equilibrium factors. The solid calcium carbonate slowly disappears as such, and enters into solution in the soil water as the bicarbonate. Provided that calcium carbonate is in sufficient excess in the soil, equilibrium is attained for any given proportion of carbon dioxide in the gaseous environment between free carbon dioxide ; dissolved carbon dioxide ; carbon dioxide ; carbonic acid in solution ; solid calcium carbonate, and dissolved calcium bicarbonate.

Calcium bicarbonate is a very soluble compound. It is also ionized in solution to the extent of about 85 per cent. into ions of calcium and of bicarbonate (HCO_3'). Further, it has been proved that a solution of calcium bicarbonate possesses an alkaline reaction towards indicators by reason of the slight increase in hydroxyl-ion concentration which it produces when dissolved in water, due to the hydrolysis of bicarbonate-ions, thus—

(v) $HCO_3' + H_2O \rightleftarrows H_2CO_3 + OH'$.

Let us now consider the effect of gradually increasing the percentage of carbon dioxide in the gaseous environment of a soil containing calcium carbonate in contact with the soil solution in which dissolved calcium bicarbonate is present in equilibrium with the other units of the system. First, more carbon dioxide dissolves, and this causes an increase in the amount of carbonic acid already present. This in turn brings about an increase in hydrogen-ion concentration sufficient to suppress the concentration of hydroxyl-ion due to hydrolysis as indicated by equation (v) above, and thus to reduce the alkalinity of the solution, until eventually such a proportion of carbon dioxide in the gaseous environment is reached to give the soil solution a neutral reaction.

Suppose that when this stage of neutrality in the bicarbonate-carbon dioxide system has been attained, an additional number of hydrogen-ions are introduced into the system by the addition of a small amount of some acid. The immediate effect

of this will be to lower the concentration of HCO_3' by combining with these ions to form molecules of the feebly-ionized carbonic acid. The latter compound will in part decompose into carbon dioxide and water, and some carbon dioxide will escape into the gaseous environment, until equilibrium in the whole system has been restored. The added hydrogen-ions are therefore soaked up, as it were, and do not appreciably alter the acidity of the soil solution. The bicarbonate—carbon-dioxide system is thus comparable with the sodium—acetate-acetic acid system already described, and the bicarbonate herein acts as a buffer in maintaining the hydrogen-ion concentration of the soil solution at a nearly constant value.

In a similar manner, the addition of a small amount of alkali to the bicarbonate—carbon-dioxide system brings about no appreciable change in reaction, because the extra hydroxyl-ions introduced reverse the hydrolytic action expressed by the equation. $HCO_3' + H_2O \rightleftharpoons H_2CO_3 + OH'$, and the increase in HCO_3' concentration is balanced by the formation of more calcium bicarbonate molecules by suppressing the dissociation of this compound.

It is therefore possible for a soil to contain an appreciable amount of bicarbonate and carbonate and yet to possess a soil solution exhibiting a degree of hydrogen-ion concentration above that represented by neutrality, for the various acidic compounds in an acid soil may yield hydrogen-ions in sufficient number to bring about an accumulation of excess of these ions in spite of the buffering effect of the carbonates in the system in equilibrium. It is the bicarbonate and the carbonate found up as it were in this system that are detected when an acid soil is subjected to chemical analysis in estimating its carbonate content.

(*b*) *The phosphate buffer system in soils.*

The presence of phosphates in the soil solution, just as in the case of blood, etc., may also cause a buffering effect, for, by considerations similar to those brought forward in explaining the buffer action of the bicarbonate system, it can be shown that a solution containing monosodium phosphate (NaH_2PO_4) and di-sodium phosphate (Na_2HPO_4) can possess a degree of hydrogen-ion concentration which is altered but slightly by the addition of small amounts of acid or alkali.

(*c*) *Other buffer systems; the effect of soil organic matter.*

It may be stated as a generalization following upon the facts already outlined, that all salts of strong bases (such as potassium sodium and calcium), and weak acids (such as carbonic, phosphoric, and boric acid, and most organic acids) can act as buffers because they yield hydrogen-ions by hydrolysis when placed in water. Further it can be shown that salts of weak bases and strong acids also possess buffer properties in solution. The common factor that makes buffer action possible in all these cases is the slight electrolytic dissociation which weak acids and weak bases exhibit in solution.

Amphoteric compounds owe their buffer properties to the fact that they can act either as weak acids or as weak bases under different conditions. The importance of proteins as amphoteric buffers in physiological liquids, such as plant saps, animal tissue juices and bacterial culture media, has frequently been pointed out in recent work, and their importance in soils is now also being recognized as furnishing an explanation of certain of the distinctive properties shown by soils rich in organic matter.

Thus Stephenson [71], basing his arguments on the chemical constitution of the proteins and their decomposition products, maintains that organic matter in soils is not likely to produce acidity, except when anaerobic conditions due to water-logging prevail, but will rather tend to prevent an increase in acidity due to other causes. He also showed [73] by pot experiments, that dressings of highly nitrogenous organic compounds have the effect of decreasing soil acidity. Coville [16] has stated that decomposing leaf-mould liberates acids, but Noyes and Yoder [51] hold that such acidity is due chiefly to carbonic acid weakly held by the organic matter. On the whole, it seems fairly well established that organic matter in normal well-drained soils tends to regulate the reaction of the soil solution by buffer action, and thus to prevent excessive concentration of hydrogen-ions rather than to augment it.

(B). THE RELATION OF TRUE SOIL ACIDITY TO PLANT GROWTH.

It is usually maintained by practical agronomists that soil acidity is harmful to most cultivated plants, and that for a soil to exhibit maximum productivity, it should contain a sufficient amount of lime to give a neutral or alkaline reaction. These beliefs are reflected in the adage that 'a limestone country is a rich country', and in a statement by the late Director of the Rothamsted Station that any soil containing less than 1 per cent. of calcium carbonate will benefit by liming.* If instead of the term *acidity* we substitute *sourness*, as defined and discusssed in the introductory to this paper, the above initial statement becomes admissible.

When acidity is considered in its physico-chemical sense, it can be shown that soil acidity, if unaccompanied by other inhibiting factors, is not *per se* ordinarily the limiting factor to plant growth in sour soils. The common occurrence of fertile soils exhibiting acidic reactions towards indicators, and therefore containing in their soil solutions a concentration of hydrogen-ions greater than that possessed by pure water, has been pointed out by numerous investigators, for example, Gillespie [24], Hoagland and Sharp [38] and Plummer [57]. Hoagland has described [36] several Californian soils which although giving pH values varying from 4·5 to 6·0, support very good crops of barley, oats, beans, potatoes, corn, etc. Moreover these soils were found to produce nitrates at a rapid rate, so that bacterial activity was by no means lacking in them.

1. THE EFFECT OF ACIDITY ON THE GROWTH OF SEEDLINGS AND ON THE GERMINATION OF SEEDS.

Recent work has shown that many agricultural plants can grow successfully in nutrient solutions possessing a considerable

*Hall, A. D. 'Fertilizers and Manures' London. John Murray: 1st Edition, 1909, p. 253.

degree of acidity. Thus Hoagland [35] grew barley seedlings in nutrient solutions of pH value 5·0, and found that the acid reaction was in no way injurious to the plants. Similarly Breazeale and Le Clerc [6] found that wheat seedlings were unaffected by a degree of acidity much higher than that exhibited by many sour soils. Still more recently, Salter and McIlvaine [66] have established the optimum reaction which favours the growth of seedlings of wheat, soy bean and alfalfa. They found this to be a reaction expressed by pH 5·94 in their experiments with nutrient solutions. For maize, the optimum pH value was similarly found to be 5·16. The limits of hydrogen-ion concentration within which seed germination could proceed were fixed at the pH values 2·96 and 7·71, so that a slightly acid reaction was found most favourable to germination in all the species examined. Certain other investigations, however, have yielded results somewhat conflictory to those recorded above. Thus Von Brehmer found that lime increases the germinating capacity of the seeds of a number of Phanerograms, and Claudell and Crochetell that an acid reaction is injurious to germinating seeds. Similar results were obtained by Tolf. (See Salisbury, 65 p. 215.) It would appear therefore that the beneficial or injurious effect of acidity on the germination of seeds varies with the species of plant which produces those seeds.

On the whole the facts indicate that the physiological processes that go on in soil and plant, and which find their final expression in the absorption by the plant roots of various ions that are essential for nourishment, are markedly modified by the presence of an excess of hydrogen-ion.

The influence exerted by hydrogen-ion in this connection would thus appear to be one phase of the vast question of the physiological balance in the nutrient solution of the different ions absorbed by plants, such balance being essential to the production of optimum growth. A great deal of research work has been performed in this domain, and the facts so far discovered are so numerous and difficult to correlate that a general discussion of the subject would be impossible in this paper. The main features of the question of physiological balance of the soil solution and the effect of manures on it will possibly be outlined in another paper shortly to appear in this journal. It may be relevant to our subject, however, to state a generalization recorded by Hoagland [37] that, in solutions of an acid reaction represented by a pH value of 5·0 to 5·5, the absorption by plant roots of various ions, notably ions of calcium, nitrate-ions and phosphate-ions, is greater than in approximately neutral solutions (pH 6·8) of similar composition and of the same total concentration.

This conclusion is somewhat discountenanced by the results of plant nutrition studies carried out at the Maryland Experiment Station, where McCall and Haag [47] have recently shown that the observed variation in plant growth with the different types of nutrient solutions used could not be definitely correlated with differences in the hydrogen-ion concentrations of the

solutions. A great deal of research work is nowadays being performed on the physiological aspects of plant growth and its relation to the composition and concentration of the soil or nutrient solution. Doubtless the true significance of the hydrogen-ion in these relationships will in due course be finally established.

2. THE EFFECT OF ACIDITY ONTHE BENEFICIAL MICRO-ORGANISMS IN THE SOIL.

It is well known that the majority of the processes that are connected with the decomposition of plant residues in the soil, including those that are especially concerned in the nitrogen-cycle, are controlled by the activities of micro-organisms, many species of which have been isolated and described. Whereas little is yet known of the life histories and mode of action of most soil micro-organisms, certain of the bacterial species that control nitrification (e.g. Nitrosomonas, Nitrobacter) and nitrogen-fixation both by free-living forms (e g Azotobacter, Clostridium) and by symbiotic forms which produce nodules on the roots of leguminous plants, (e.g. Pseudomonas, Rhizobium), have been the objects of detailed study. The formation of ammonium compounds (ammonification) from the complex nitrogenous organic compounds present in plant residues, is governed by numerous species both of fungi and of bacteria, each of which controls one stage of the decomposition Only a limited number of these specific organisms have been so far described, but studies of the fungi and bacteria of ammonification, considered as a whole have yielded some information as to the conditions governing their activities.

Detailed investigations of the effect of the reaction of the medium on the activities of certain of the micro-organisms concerned in the main processes of the nitrogen-cycle in the soil, as outlined above, have been made, chiefly in nutrient solutions We may describe the findings of these investigations in separate sections.

(a). Numerous workers have observed that *ammonification* is prevalent in soils of all kinds, and that acidity seems to have no particularly adverse effect upon the life of the micro-organisms that are responisble for it

Thus Coville [15] has shown that many soils acid to litmus contain large amounts of ammonium compounds. Fred and Graul [20] have also shown that the formation of ammonium compounds from casein takes place so rapidly in an acid soil that for several weeks after the nitrogenous substance is added, the production of nitrates is not limited by lack of ammonium compounds. Kopeloff [13] has dealt with the part played by certain soil fungi in ammonification, and has reviewed the literature of this branch of the subject. His own researches show that ammonifying fungi can withstand a much greater intensity of acidity than can ammonifying bacteria, and that in acid soils, these fungi may be instrumental in maintaining the rate of production of ammonium compounds in the soils.

(b). With *nitrification* the case is somewhat different from the last. In his classical researches on the nitrification process in soils, Warington came to the conclusion that the presence of a base with which nitric acid formed in the process can combine is a necessary condition. Dehérain [18] in 1894 stated that 'the nitric ferment does not act in an acid medium,' but he also noted that nitrification may go on in a soil deficient in lime. As long ago as 1872, Houzeau [34] reported nitrification in an acid soil. In 1908, Hall, Miller and Gimingham [30] found nitrates in a soil of marked acid reaction, but they considered that the presence of small isolated particles of calcium carbonate made possible the activity of nitrifying bacteria in the immediate vicinity of these particles. Since then many other workers have recorded nitrification in acid soils.

(c). *Nitrogen-fixation* by free-living bacteria. Christiansen, in Denmark, has investigated the prevalence of *Azotobacter* in soils of varying degrees of acidity. He found that this organism was especially sensitive to the presence or absence of lime in the soil, and proposed using *Azotobacter* as an indicator for giving information as to the lime requirements of soils. Christiansen has compared [10] the *Azotobacter* test with the litmus test for soil acidity, and with the commonly used lime-requirement methods. He noted a close correlation between intensity of acidity, as gauged roughly with litmus, and the presence or or absence of *Azotobacter*.

Bear [4] has summarized the literature on the subject up to 1917, and presents the results of his own experiments in which he has verified many of the facts above mentioned. Bear found that the several types of soil organisms known to be beneficial to plant growth vary in their response to liming. Ammonification apparently proceeds in almost any soil whether deficient in lime or not; nitrification proceeds best in soils that are not deficient in lime; nitrogen-fixation by non-symbiotic organisms, such as *Azotobacter*, is markedly increased by increase in the lime content of a soil.

In the investigations outlined, comparisons have been chiefly made between micro-organic activity in soils and lime requirement. No very exact data as to the *intensity* of acidity in the soil or culture solutions used in these researches are presented. Gainey, however, in 1918 [23] attempted to correlate the activity of *Azotobacter* in soils with the hydrogen-ion concentration of the soil solutions. He used indicators to obtain the pH values for the soils examined. His results show that there is good reason to believe that *Azotobacter* will not thrive well in soils whose acidity is greater than that represented by the pH value 6·0.

(d). That bacteria which are able to fix atmospheric nitrogen when living in symbiosis with certain leguminous plants are markedly affected by the reaction of the medium in which these plants grow, has also been demonstrated in a limited number of investigations. An historical review of these researches is given in a paper by Fred and Davenport [19]. Beijerinck in 1888 showed that *Rhizobium leguminosarum* is injured in a medium of minimum acidity equivalent to an acidity of N/50 concentration. Numerous other workers have since made somewhat conflictory

statements, but much of the earlier work requires revision in view of recent researches on the effect of hydrogen-ion concentration on bacterial processes as contrasted with that of total acid. Fred and Davenport (*loc. cit.*) worked with pure strains of *Rhizobium leguminosarum* obtained from different leguminous plants, and found that the critical pH value for each of these strains varies considerably. Thus for lucerne (alfalfa) and sweet clover, the critical pH value was found to be 4·9; for peas and vetch, 4·7; for red clover and common beans, 4·2; for soya beans and velvet beans, 3·3, and for lupins 3·15. Each of these plants is apparently able to thrive in soils of varying degrees of acidity by reason of the adaptability of their special strains of nodule bacterium to the reaction of the soil solution.

Although many investigations, such as these outlined above, have been carried out with bacterial cultures in nutrient media, as yet these studies have not been supplemented by actual observations in the field. It seems quite possible that certain acid-resisting bacterial strains may exist in soils. Indications of their activity have been noted in culture studies, and their presence in certain soils of extreme acidity must be postulated if one is to explain the nitrogen transformations which go on in such soils.

3. THE EFFECT OF ACIDITY ON PLANT DISEASE ORGANISMS.

The relation between the intensity of acidity of the medium and the life of beneficial soil organisms, as described in the last section, may be extended to include other soil organisms of pathogenic importance. Bacteriologists and mycologists have long been aware of the dependence of living cells on the maintenance of a limited, and in many cases of a very strictly limited, hydrogen-ion concentration in the environment, and have used this knowledge in studies on the life-histories and methods for the control of organisms responsible for certain animal and plant diseases.*

Farmers in temperate countries have suffered for many years the scourges of an organism which is prevalent in soils lacking lime and which produces a disease known as 'finger and toe' in cruciferous crops, such as turnips and cabbages. Voelcker in England showed in 1859 that liming, by correcting the acidity of infected soils, brought about a surpression of this disease. Another disease of common occurrence in temperate countries, and dependent for its incidence and spread on an acid soil condition, is the scab of potatoes. Recently the existence of a definite limit of acidity has been demonstrated for this organism by Gillespie [25], who worked in the laboratory with cultures of the organism. Studies of the field conditions in relation to potato scab were also undertaken by Gillespie and Hurst [26], who showed that the scab organism does not thrive well in soil whose soil solution is more acid than an intensity represented by pH 5·2. As a corollary to this discovery, Martin [15, 16] showed that potato soils with alkaline reactions and

* For a summary of literature and references see (11) p.p. 220-23, and (12) pp. (1-11).

growing scabby tubers could be corrected by the application of suitable dressings of sulphur. The oxidation of this substance in soil, under the control of certain sulphur bacteria, gives rise to sulphuric acid, which neutralizes the excess of lime in the soil, and leaves it with an acid reaction.

Exactly how far studies similar to the above on the relation between soil reaction and the spread of other plant diseases may yield important results, yet remains to be seen, for doubtless many other investigations in this branch of soil science will be attempted in the near future.

III. DEFICIENCY IN CALCIUM COMPOUNDS AS A FACTOR IN SOIL SOURNESS.

That the most general characteristics of sour soils is their deficiency in easily soluble base has already been noted in the Introductory. This deficiency of base is responsible for the accumulation in the soil solution of an excess of hydrogen-ion produced by the dissociation of acidic substances present in sour soils. When a base such as calcium carbonate is added to these soils in sufficient amount to disturb the equilibrium of the bicarbonate-carbon-dioxide system, as described in the section on buffer action, it completely suppresses the excess of hydrogen-ion by yielding an increasing supply of hydroxyl-ions.

The extent to which the infertility of sour soils is due to the actual presence of excess of hydrogen-ion rather than to the absence of a necessary concentration of calcium-ion in the soil solution, other inhibitory factors being absent, has only recently been studied in detail. The facts presented in the last section indicate that the most desirable reaction of the soil solution, in so far as the nutrition of the plant is concerned, is probably one of marked acidity, corresponding to a pH value lying between 5·0 and 6·0. The proper development of the nitrogen-transforming organisms occurring in soils, however, apparently requires an optimum reaction considerably less acid than this, so that in actual agricultural practice a compromise has to be allowed, unless an attempt is being made to combat some disease located in the soil by impressing some definite reaction upon the soil solution.

Besides influencing the reaction of the soil solution, calcium carbonate in soils exerts a marked influence on the texture, for it gives rise to the soluble bicarbonate which flocculates colloidal clay. This subject, which belongs to the domain of soil physics, need not be discussed here.

1. THE ROLE OF CALCIUM IN PLANTS.

That calcium compounds are required by plants in considerable amounts is indicated by analyses of plant dry matter. Parker and Truog [55] recorded the compositions of thirty-four species of plants with respect to certain elements, and concluded that there exists a close relationship between the calcium and the nitrogen content of these plants. Members of the Gramineae were observed to possess a relatively low calcium-nitrogen ratio

(average figure 0·306 per cent.). These plants are known in the field to possess considerable tolerance to soil-acidity. Leguminous plants and other species which generally respond markedly to liming, and are sensitive to acidity, were observed to possess higher calcium-nitrogen ratios (average figure 0·553 per cent.). These results are taken to indicate some undetermined difference in the metabolic processes of the two groups of plants.

Calcium compounds are needed by plants for at least two purposes: (1) to furnish the comparatively small amounts of calcium necessary to the plant in the synthesis of proteins and other plant substances, and (2) to neutralize and precipitate acid substances that are present in the plant sap, and which are manufactured as by-products of katabolism. Thus the oxidation of proteins gives rise, amongst other products, to organic acids, of which formic, acetic, oxalic, succinic, malic, and caprionic are the chief. Plants high in proteins would therefore be expected to produce large amounts of waste acids products, and consequently to show high lime requirements. This may explain the large calcium content of leguminous plants, etc., which contain an exceptional amount of protein nitrogen [55].

Any kind of soluble calcium salt in a soil would apparently serve to supply the direct nutritive needs of a plant, but the second purpose would seem at first sight to require that the calcium compound should be the bicarbonate alone. Calcium bicarbonate, being a very soluble salt, and possessing a high degree of dissociation in solution, is able to yield a considerable concentration of calcium-ion and of bicarbonate-ion (HCO'_3) to the soil solution. It may be assumed that plant roots are able rapidly to absorb both calcium-ions and bicarbonate-ions from the soil solution. The calcium-ions, besides playing other important rôles in plant metabolism, may precipitate in the plant sap certain acid ions, such as the oxalate-ion, because they form molecules of insoluble compounds with them. The bicarbonate-ions, on the other hand, may suppress the concentration of hydrogen-ion due to the dissociation of acidic waste products in the sap Carbonic acid would be formed; this in part decomposes, giving carbon dioxide, which might escape into the intercellular spaces and be excreted by the plant. In this way calcium bicarbonate may be able to precipitate and to neutralize the acidic waste products formed during metabolism. In view of the fact that many plants will grow in media of definite and appreciable acidity, it would appear that there is some flaw in the theory as propounded above, and that there is no need to postulate that plants must absorb both calcium-ions and bicarbonate-ions in order to maintain a constant and inexcessive degree of hydrogen-ion concentration in their sap. It is quite possible that the only essential factor in the case is that a sufficient number of calcium-ions should be available in the plant sap to lower the degree of dissociation of the acid waste-products by forming with the acid-ions calcium compounds of low ionization constants, or of low solubility. In this way the calcium-ion alone may conceivably be capable of reducing the acidity of plant sap and preventing the accumulation of harmful acid waste-products.

The whole question of the rôle of calcium in the complex processes that go on within the plant body is somewhat difficult

to understand ; it need not be more fully discussed in this place The fact remains clear that plants require a considerable supply of calcium over and above that which enters into the composition of the body substances.

Truog [75] sums up the situation by stating that different plants have different lime requirements which refer to the 'actual lime needs of the plant itself, especially as to the use and rate at which lime must be secured from the soil by the plant for normal growth' (*ibid* p. 192). Thus, if a plant has a large lime-requirement, then the liberation of calcium-ions to the soil solution and its absorption by the plant roots must be rapid in order to meet the needs of that plant. The three main factors which, according to Truog, determine the lime-requirement of a plant are: (a) its normal lime content, (b) its rate of growth, (c) its feeding power, as determined by the character and extent of its root system. The first two factors operate in one direction, whilst the third operates in the other direction, the actual lime-requirement therefore being the resultant of all the three.

2. THE CORRELATION BETWEEN THE REACTION OF PLANT SAP AND THAT OF THE SOIL SOLUTION.

Truog (*ibid*) has presented much experimental evidence to show that there exists a close correspondence between the lime-requirements of numerous species of plants and their response to the liming of acid soils that support them, or reciprocally, to their ability to withstand acid soil conditions.

As a corollary to these conclusions, Truog and Meacham [76] have estimated the degree of acidity of the expressed sap of several species of plants grown on acid soils, and state that 'unquestionably soil acidity in many cases affects the acidity of the juice or protoplasm of these plants by limiting the supply of available lime' (*ibid*, p 473). This is presumably because the by-products of plant metabolism are in the main acidic in nature.

The whole question, however, needs to be placed on a sound physiological basis, for there are certain objections to the statements made and to the experimental methods employed by the above-named investigators. Thus the acidity of the plant saps was estimated on the saps that were obtained merely by the application of pressure, and this would not be expected to yield liquids that are identical in composition or concentration with the contents of the cell vacuoles.† That the intensity of acidity of the cell sap of plants is an important factor in the regulation of the activities of the enzymes present in it has been shown by physiological research.* Each species of plant contains cell sap whose hydrogen-ion concentration appears to be specifically adapted to the physiological processes of that plant, and is maintained at a constant value mainly by the buffering effect of certain solutes in the sap.

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† See 'Some recent researches in Plant Physiology,' W. R. G. Atkins. London, 1916: Macmillan.

* For references see Clark's 'Determination of Hydrogen-ions' 11 p. 230, and Clevenger,[13] pp. 217-18.

The question of the acidity of plant saps in relation to various environmental factors governing plant growth has also been investigated by Clevenger [15] and by Haas [29]. The former found a definite correlation between the intensity of acidity in the sap of roots of certain plants, and that of the soil solution of the acid soils in which they were growing. No simple correlation was found for the sap of stem and leaves. In some cases the addition of lime to the soils, by providing a stimulant to the growth processes of plants, appears to cause a rise in the rate of production of acid substances within the plant tissues in stem and leaf, and hence to produce a higher intensity of acidity in the sap of these tissues. The reaction of the root sap under this treatment may remain unaltered.

Although the relationships between soil conditions and the anabolic and katabolic transformations that occur in plants cannot yet be said to be clearly established, there is here an interesting field of research which promises results of far-reaching importance

That the total calcium content of a soil is one of the major factors influencing plant growth is no longer doubted, but only the most careful and thorough investigation can be hoped to establish the cause of the unproductivity of any particular example of a sour soil as being definitely due to deficiency of calcium. The work of Shedd [70] on the lime-deficient soils of Kentucky, for example, led him to conclude, from the fact that the more fertile of these soils contained the higher proportions of cf calcium, that the cause of infertility here was lack of calcium No detailed analysis of other factors that might have been responsible for low productivity, such as the presence of excess of hydrogen-ion or of toxic metallic-ion, was attempted, so that Shedd's conclusion as published, would seem to need qualification. It would appear to be especially difficult to establish the unproductivity of any particular sour soil as being due to a deficiency of calcium compounds rather than to the inhibiting effect to plant growth of the several other factors presented by sour soils, and correlated with such calcium deficiency.

IV. THE TOXICITY OF ALUMINIUM, IRON, AND MANGANESE AS A FACTOR IN SOIL SOURNESS.

1. THE TOXIC EFFECT OF ALUMINIUM, IRON, AND MANGANESE ON PLANT GROWTH.

Many of the earlier workers on soil acidity problems observed that, when certain soils were extracted with solutions of neutral salts, the extracts were acid in character, and furthermore, that they contained a notably high concentration of aluminium, iron, and occasionally manganese.

Veitch in 1904 connected the two results, and attributed the presence of acid in the extracts to the hydrolysis of aluminium and iron salts brought into solution by basic exchange between certain soil minerals and the neutral salts added. (See p. 47).

Abbott, Conner and Smalley [1], during their examination of certain Indiana sour soils in 1913, concluded that the infertility of

these soils was largely due to the toxic effect of aluminium in the soil solution. They obtained water extracts of the soils, and showed that the reaction and toxicity of these extracts could be exactly matched in nutrient solutions which included aluminium nitrate and nitric acid in their make up.

Hartwell and Pember [32] in 1918 demonstrated that the extracts of certain sour soils which had been receiving continuous dressings of ammonium sulphate, and which could support only very inferior crops of barley, could be imitated by nutrient solutions containing aluminium sulphate, but not by nutrient solutions to which sulphuric acid had been added. This result definitely established the unproductiveness of the barley soils as being due to an excessive concentration of aluminium-ion and not to hydrogen-ion.

Mirasol in 1920 [45] performed an interesting series of experiments in which he demonstrated, amongst other facts, that aluminium salts, in the absence of calcium compounds, are highly toxic to sweet clover grown in sand-cultures. The medium was watered with solutions of aluminium salts of such composition that they possessed a reaction equivalent to that of an average sour soil, such as those subsequently examined in the investigation. Insoluble aluminium hydroxide ($Al(OH)_3$) mixed with the sand was shown not to have any toxic effect towards the plants. Furthermore, Mirasol showed that certain sour soils that had previously been submitted to the leaching action of a neutral salt solution (potassium nitrate), so that a large amount of the more easily decomposed aluminium compounds in them had been removed, were better able to support the clover crop. Whilst iron and manganese are probably contributory factors in the infertility of certain sour soils, Mirasol considers that the preponderance of evidence points to aluminium as the determining factor, at least in the cases investigated by him.

Plant physiologists have demonstrated by numerous nutrient solution experiments that, whereas aluminium-ion in low concentration may have some stimulating effect on plant growth, it becomes markedly toxic when it exceeds the concentration of aluminium-ion occurring in a solution of aluminium sulphate containing 0·0342 grams of the compound per litre, viz. a solution of 0·0001 normality. (Mirasol, [45] p. 160.) The toxicity of iron and of manganese salts has also been demonstrated and standardized in a similar way. There would appear to be no doubt, therefore, that, in those sour soils that contain toxic amounts in the soil solution of aluminium-ion (or of iron or manganese-ion in toxic amount), infertility is in the main due to the presence of excess of these organic toxins, and not necessarily to the presence of excess of hydrogen-ion which, for reasons already explained, usually accompanies them.

In actual practice it is impossible to estimate the concentration of aluminium-ion (or of iron or manganese-ion) in a soil solution or extract with any degree of precision. As far as the writer is aware, no accurate method for the determination of the concentration of these metallic ions in solutions, along the lines of the electrometric hydrogen electrode method for hydrogen-ion estimation, has yet been elaborated. The only

simple way in which toxicity due to aluminium-ion etc. in a soil solution can be demonstrated is first to determine the total quantity of the element in a certain volume of the solution, or in an equivalent volume of the soil-extract by conventional gravimetric or volumetric means, and then to compare the figure obtained in this quantitative estimation with the results of analyses of nutrient solutions containing varying amounts of the toxic elements, and possessing known degrees of toxicity towards plant growth. An alternative way is to use the water extract of the sour soil whose unproductivity is suspected to be due to the presence of inorganic toxins, as a nutrient medium in which to grow test plants, or to water sand cultures of the test plants.

2. THE ORIGIN OF SALTS OF ALUMINIUM, IRON, AND MANGANESE IN THE SOIL SOLUTION.

Aluminium occurs in the mineral portion of soils chiefly in certain complex silicates of which the felspars and certain of the ferro-magnesian minerals (e.g. mica, augite, hornblende, etc.) are the most abundant. It also occurs as phosphate and oxide, and possibly also as various hydroxides. Iron occurs chiefly in ferro-magnesian minerals (e.g. biotite, augite, hornblende, olivine), and as oxide (magnetite, etc.) and hydroxide (limonite). Manganese is of rare occurrence, and is occasionally found in ferro-magnesian minerals and less commonly as oxide.

Soil analyses have shown that the largest quantity of the three metals mentioned is present, in the finest particles of the soil. During the weathering of rocks rich in silicate minerals a residue containing a large proportion of kaolinite is left (see p. 47). Under certain conditions lateritization rather than kaolinization goes on, and the ultimate products of weathering them consist chiefly of aluminium hydroxides and iron hydroxide.

Of the three known aluminium hydroxides, gibbsite ($Al_2O_3 3H_2O$) alone is soluble in dilute acids and alkalies. None of the hydroxides dissolve in water (Olsen, quoted by Mirasol,[48] p. 164). In sour soils, which contain in their soil solutions injurious amounts of aluminium-ions, gibbsite must therefore be the compound which chiefly gives rise to these ions, for all the other aluminium compounds enumerated above are either quite insoluble and stable, or are only very slightly decomposable under the conditions that occur in soils. There has been some doubt cast as to the actual occurrence of gibbsite and the other hydroxides of aluminium in soils, especially soils of northern latitudes. Cameron and Bell, for instance, state that neither gibbsite nor bauxite occur in the great majority of the United States soils [9]. Other investigators have brought forward evidence against this conclusion, and Mirasol ([48] p. 165), summing up the data, expresses the opinion that, at least in sour soils containing toxic amounts of aluminium, the compound furnishing the aluminium is undoubtedly gibbsite. In tropical countries, the presence in soils of aluminium hydroxides, including the easily decomposable gibbsite, is more than likely, since lateritization is the type of weathering that commonly goes on in those countries.

According to Hilgard *, in order to detect the presence of aluminium hydroxides in soils by chemical analysis, as contrasted with the actual identification of the minerals by mineralogical examination, the percentage amounts of aluminium oxide (alumina) and of silica, soluble in hydrochloric acid under the conditions observed in conventional soil analysis, should first be estimated. Now silica and alumina are combined in kaolinite which, apart from the hydroxides, is the chief form in which aluminium occurs in soils. In kaolinite, silica and aluminia are combined in the ratio of 46 : 40 per cent. The remaining 14 per cent. is water of hydration. If the analytical figures show an appreciable amount of acid-soluble aluminia over and above that required to combine with the acid-soluble silica to satisfy the quantitative ratio stated, the conclusion may safely be drawn that free aluminium hydroxide exists in the soil, and that this, because of its solubility in the acid, is probably gibbsite. In this way, then, one may gain information as to the cause of infertility in cases of sour soils that are deficient in easily soluble bases, for if the analytical figures obtained in the conventional chemical analyses of such soils exhibit the particular quantitative relationship between aluminia and silica stated above to be indicative of the existence in those soils of free aluminium hydroxide, it is more than likely that their soil solutions will contain aluminium in toxic amount.

Spurway [72] has carried the application of this principle to a further conclusion in his examination of certain glacial sour soils of Michigan. He found a definite correlation between the ratios of calcium oxide to iron and aluminium oxides soluble in dilute hydrochloric acid and the reaction of the soils. All the soils with acid reactions to litmus gave ratios $CaO : (Fe_2O_3 + Al_2O_3)$ above 1 : 1·3, and all soils with alkaline reactions gave ratios below this figure

Howard [39], in a study of the variations in the intensity of soil acidity occasioned by the applications of dressings of sodium nitrate and ammonium sulphate to certain soils of the Rhode Island Experiment Station, came to the conclusion that in the acid unlimed soils, iron and aluminium oxides as bases, partly take the place of calcium and magnesium oxides in the limed soils. Furthermore, the concentration of hydrogen-ion in the soil solution of the unlimed soils receiving ammonium sulphate was found to be very similar to that produced by the addition of certain amounts of aluminium salts to neutral buffer solutions. Howard used Gillespie's colorimetric method for determining hydrogen-ion concentration. The conclusions appended to Howard's paper are worthy of quotation *in extenso*, not only because they explain the effect of continued treatments of soils deficient in easily-soluble bases with dressings of ammonium sulphate, but also because they sum up the reasons why certain sour soils possess an acid reaction, as well as a varying concentration of aluminium-ion and of iron-ion in the soil solution. Howard writes : 'The acidity in a soil caused by the long-continued use of ammonium sulphate is the result of a change in the ratio of acids to bases. The position normally occupied by

*Hilgard's 'Soils.' Macmillan. New York, 1918. p. 101.

the stronger bases such as calcium and magnesium, has been taken by the weaker bases such as iron and aluminium. The neutrality of the soil solution can no longer be maintained since salts of these weak bases dissociate.* Free acids resulting from this dissociation is accompanied by a definite concentration of hydrogen-ions' (*loc. cit.* p. 320).

Comber [1] has accepted in principle the above conception of the causal association of iron and aluminium-ions and hydrogen-ions in the soil solution of sour soils, and has directed attention to it in support of a quantitative test for sour soils which he has discovered. Comber applied an alcoholic solution of potassium thiocynate to samples of Yorkshire soils, and found that those soils which, in a previous examination had been found to be deficient in easily-soluble base by the Hutchinson-McLennan lime requirement method, imparted a blood-red colour to the reagent through the formation of ferric thiocyanate by the exchange of potassium-ion for ferric-ion in the soil solution.

Let us now consider how aluminium, iron, and manganese-bearing minerals in the soil may give rise to ions of these metals in the soil solution. Analyses of soil extracts have shown that the soluble chlorides, sulphates, and nitrates of the three metals may all be present in the soil solution. The amount of chloride and of sulphate will naturally be limited by the amount of chlorine and of sulphur in the soil. Under certain conditions, soils rich in sulphur may contain considerable quantities of aluminium and manganese sulphates, as was shown by Ames and Boltz [2].

Nitrification is a normal process in soils, and when most active, comparatively large quantities of nitrates of aluminium, iron, and manganese may be formed, provided that other more easily soluble bases, such as calcium and magnesium compounds are not present to excess. (Potassium and sodium compounds such as the carbonates liberated during rock weathering can never neutralize all the nitric acid formed during nitrification, since these compounds are extremely soluble, and are usually leached out of the soil, unless absorbed by plant roots, almost as fast as they are formed.)

The conclusion reached by a consideration of these facts is that many sour soils that is soils deficient in easily soluble bases (calcium and magnesium compounds), may be expected to contain in their soil solutions an appreciable concentration of ions of aluminium, iron, and manganese, either together or severally. When this concentration of ions rises above a certain figure, the soils will be more or less infertile to most agricultural plants because of the toxicity of these ions in the soil solution. Accompanying the ions of aluminium, iron, and manganese, there will always be a corresponding concentration of hydrogen ion in excess of that normally present in pure water. The sour soils will thus show an acid reaction towards indicators.

It does not necessarily follow, however, that the *total* hydrogen-ion concentration in the soil solution of all sour soils

* i. e. hydrolytic dissociation, e. g, $Al_2(SO_4)_3 + 6\ H_2O \rightleftarrows 2Al(OH)_3 + 3H_2SO_4$

is due entirely to the hydrolysis of salts of aluminium, iron, and manganese. Certain peat soils, for example, may possess acidic soil solutions because of the ionization of organic acids present in them. Badly drained soils rich in humus may show this characteristic through lack of sufficient aeration whereby the organic acids are prevented from becoming oxidized (p. 75). Mineral soils also may show an acid reaction towards indicators, owing to the presence of definite mineral acids in them (p. 47). Knight [43], for example, has demonstrated the possibility of certain acid mineral soils containing in the soil solution hydrogen-ions due to the ionization of inorganic mineral acids, in addition to those due to hydrolysis of aluminium, iron, or manganese salts.

3. THE SPECIAL CASE OF MANGANESE IN THE SOILS.

The peculiar relationship of manganese to plant growth is worthy of separate mention, since recently much stress has been laid on the rôle which manganese compounds play in the plant and in the soil.

It has long been known that manganese occurs in a great many plants LeClerc in 1872 found the element in most of the soils and plants examined by him. In 1896, Bertrand showed that manganese plays an important part in the process of oxidation in plant metabolism. This aspect of the subject will be more fully considered in the next section.

Although numerous field trials have demonstrated the undoubted manurial value of manganese salts applied to certain kinds of soil, it has been found that dressings of over 40 lb. of manganese per acre are usually detrimental rather than beneficial.

Cases of sour soils which owe their unproductivity to the presence of excessive amounts of manganese in the soil solution have been recorded. Funchess [21] was given reason to suspect that certain soils of the Alabama Experiment Station were infertile from this cause, although later [22] he somewhat modified his opinion, and laid more stress on the inhibitory effect of an excessive concentration of hydrogen-ion in the soil solution presumably brought about by the hydrolysis of manganese salts chiefly. Robinson, Gardiner, and Holmes [62] summarized the results of experiments on certain sour soils in which they found a maximum amount of water-soluble manganese equivalent to 24 parts of MnO per million of soil extract. This concentration of manganese they considered to be large enough to exercise a toxic effect on the bacterial flora of the soil, and also to have a direct harmful effect on plant growth.

Mirasol's experiments [48] also indicated the importance of manganese as a toxic soil constituent. It would appear that infertility due to the presence of an excessive concentration of manganese-ion in the soil solution is of rare occurrence however, and that the element most frequently found to be toxic in soils is aluminium and not manganese.

V. THE ABSENCE OF ADEQUATE AERATION AS A FACTOR IN SOIL SOURNESS.

OXIDATION PROCESSES IN SOILS AND THE FACTORS CONTROLLING THEM.

Soils whose sourness can definitely be traced to poor aeration as the major factor responsible for their infertility, constitute an important class the study of which is of particular interest in humid tropical countries. Poor aeration is primarily caused by imperfect drainage, and this in turn is the result of many factors, of which the nature of the substrata underlying a soil, the topographical position of the area containing it, and tilth are the chief.

The tilth of a soil may be defined as that state of a soil which is decided by the relative sizes of the constituent particles, and the way in which these particles are arranged. Sandy soils in most cases possess a good tilth; clay soils in general are wet and sticky. But certain clay soils frequently exhibit a good tilth because of the aggregation of their ultimate particles into floccules, and of these floccules into crumb. It is the chief aim of the clay land farmer to build up in his soil compound particles by cultivation. This involves careful tillage, manuring with dung and green dressings, and liming. The addition of various artificial fertilizers to soils has frequently been found to result in great alterations in soil tilth. Nitrate of soda and sulphate of potash are said to destroy tilth, whereas lime frequently brings about great improvement because of the marked flocculation which it induces.

Thus the presence of lime in a soil is one of the main factors which are responsible for good tilth. Not all soils rich in lime possess a good tilth for that reason alone however, but in general, water-logged soils containing lime can be more readily brought into a satisfactory state as regards tilth by artificial drainage and tillage than can similar soils deficient in lime. In this connexion, therefore, tilth is a factor often positively correlated with the amount of lime in a soil, and consequently so also is aeration in so far as this condition is decided by tilth.

It is unnecessary to discuss the exact meaning of tilth, or to go into the physico-chemical theories that have been brought forward to explain it, since we are only concerned here with the effect which poor aeration produces on the chemical changes in soils, resulting usually in the formation of substances of acidic reaction.

The lack of ventilation in water-logged or compacted soils greatly minimises the amount of free oxygen that can come into contact with the soil constituents, so that in such soils oxidation is either altogether absent, or proceeds but slowly. The importance of oxidation in soils has been insisted upon by many investigators, notably by Schreiner and his collaborators at the United States Bureau of Plant Industry, who have shown that certain toxic organic substances tend to accumulate in soils of low oxidizing power (see 77). The very extensive research undertaken by these men is based

on the work of Whitney, who was the first to point out the important relationships that exist between fertility and the composition of the soil solution. Whitney claimed that the soil solution of almost all soils is of approximately the same composition and concentration. Hence infertility cannot be due to a lack of plant nutrients in unproductive soils ; it must therefore be due to the presence of some soluble toxin. Fertilizers were supposed by Whitney to precipitate toxins from the soil solution, and to owe their beneficial effects to this and to other indirect actions in the soil.

Pickering's investigations at the Woburn Fruit Farm [56] have clearly shown that the roots of many plants give rise to soluble toxins which adversely affect the growth of other plants in the immediate vicinity. These toxins are apparently readily decomposed in the soil, for laboratory tests failed to reveal their presence in the soil extract. The toxic effect of one plant on another was shown to be most marked in badly aerated soils. These results are in full agreement with Whitney's views.

Schreiner and his collaborators* commenced in 1907 to make a careful search in the soil for such organic compounds as could be identified. They concurrently studied the effect these and of similar compounds on plant growth in a series of nutrient culture solution experiments. Certain compounds such as dihydroxystearic acid, guanidine, vanillin salicylic aldehyde, and picolinecarboxylic acid were in this way found to be toxic to plants, and it was demonstrated that certain of these substances are almost invariably present to excess in badly drained, badly aerated, compacted, and lime-deficient soils, such as would be classified as typical sour soils. The majority of these compounds are evidently decomposition products of plant residues, or are actual plant excretions, and, being in some cases acidic in nature, are doubtless responsible in part at least, for the excessive concentration of hydrogen-ion in the soil solution of soils of low oxidizing power

Rigg [60] prepared solutions from the decay products of the rhizomes of *Nymphaea*, and found that these had a markedly toxic effect on plant growth. The solutions showed measurable acidity, but after the neutralization of the acids present, they were found to have lost their toxicity.

Dachnowski [17] has attributed the toxic effect of bog water to the presence of acidic products of the decay of plant residues in the absence of adequate aeration.

Soil oxidation has been studied in detail by Schreiner and Sullivan [68]. These investigators distinguish between the extracellular oxidation which living plant roots are apparently able to bring about at their surfaces on certain substances in the soil, and oxidation that proceeds in the soil itself. The mechanism of these oxidation processes is fully discussed, and a review of the extensive literature on the subject is given in the bulletin cited. Oxidation at the root surface and oxidation in the soil itself are probably of the same type. It is not yet definitely settled whether or no the process is controlled by enzyme activity, although the usually accepted idea up to the present time has been that oxidation by the plant and by plant extracts is due to

*See the various bulletins of the United States Department of Agriculture Bureau of Soils, especially Nos. 47 (1907), 56 (1909), 73, 74 (1910), and 87 (1912.)

oxidizing enzymes. It has been shown, however, that many, if not all, of the oxidations produced by the so-called enzymes can be brought about by non-enzymotic substances both organic (such as benzaldehyde, pyrogallic acid, quinone and certain organic peroxides), and inorganic (such as peroxides and salts of manganese, iron lead, etc.). Essentially oxidations in the soil consist firstly of the fixation of atmospheric oxygen in an active form by its entering into combination with certain organic substances with which it forms peroxides ; and secondly, the oxidation of easily oxidizable organic matter that has previously been produced by the action of micro-organisms on plant residues, by the transference to them from these peroxides of oxygen in an active or nascent state.

In the absence of oxygen, organic substances accumlate in the soil, and many of these, being of a toxic nature, inhibit plant growth and render the soil infertile.

It has been found that oxidation in the soil is increased by the addition of salts of manganese, iron, aluminium, calcium, and magnesium, especially in the presence of simple hydroxyacids, such as citric, tartaric, malic, glycollic acids and their salts. The best oxidation is obtained by the addition of manganese salts to soils. It has long been known that manganese stimulates plant growth when introduced in not too great amount into the media in which plants are rooted. It appears that certain compounds of this metal have the power of bringing about rapid oxidation, especially when combined in some way or acting in conjunction with certain organic substances, such as the hydroxyacids and their salts, already mentioned. The part played by manganese in the internal oxidation processes that go on in living plants may perhaps be accounted for in this way. Indeed, Bertrand held that many of the so-called plant oxidases, actually consist of some active complement, usually a manganese salt, combined with an activating complement which may be protein in nature.

Possibly the increased oxidative activity which proceeds in soils when manganese salts are applied to them as manurial dressings, may thus be due to the formation of oxidase-like catalists in the soil, or to the augmentation of the supply of similar catalists already present therein.

Skinner and Sullivan [1], and later Brown and Menges [2], showed that manganese, in addition to influencing oxidation, stimulates the activity of micro-organisms in the soil, especially of the bacteria of ammonification and of nitrification.

It has frequently been demonstrated, on the other hand, that excess of manganese in the soil may prove highly injurious, as has already been mentioned in the last section.

Soils whose infertility is due to the presence of toxic organic compounds formed under conditions of poor aeration may generally be made productive by proper draining, followed by the application of lime and other soil amendments, possibly including manganese compounds. The change in conditions brought about by these operations allows the oxidizing agents present in the soil to exercise their full effect, and thus to cause the destruction of the toxic substances by breaking them down into simpler and inocuous oxidation products.

It has been suggested above that this process of oxidation is controlled in every case by certain compounds present in the soil itself, but it appears from the recent work of Robbin and his collaborators [61] that, in certain cases at least, bacterial activity is the agent directly responsible for the decompositien of the toxic organic substances. Robbins has shown that there exists in soils a limited number of species of bacteria which are able to destroy vanillin. This substance is one of the toxins that has been isolated from certain soils. Those conditions which favour rapid oxidation also encourage the maxium activity of the vanillin bacteria, for good aeration and an alkaline reaction in the soil have been shown to furnish the optimum conditions for their development.

2. THE PRESENCE OF PROTOZOA IN SOILS.

No account of soil sourness would be complete without some reference to the protozoan fauna of the soil. Russell and his collaborators* have demonstrated at Rothamsted that in many soils two groups of organisms normally occur; one set includes the beneficial bacteria which play an active part in such important processes as humus formation, nitrification and nitrogen fixation, and the other set includes certain protozoa that apparently are able to destroy organisms of the first class, and may thus be detrimental in their effect on fertility in certain cases.

In well aerated, highly productive soils, protozoa are probably present in negligible quantities, but in soils that are poorly aerated and exhausted by repeated cropping, the protozoan fauna may be very prolific, and may become one of the factors responsible for the unproductiveness of those soils. Greenhouse soils are said to be especially prone to such degeneration. Infertile soils of this type have been termed 'sick' soils.

It has long been known that many soils are altered by antiseptics such as carbon bisulphide, which were first applied to soils in order to kill insect pests. It was shown in 1893 that the bacterial flora undergoes a marked change when the soil is treated with carbon bisulphide. First a great decrease in the number of organisms capable of developing on gelatin plates is noted. This is followed by a striking increase in bacteria, the number rising far higher than it was before, and the new flora having a somewhat different composition from the old. The result is found to be similar when antiseptics other than carbon bisulphide are employed. Certain sewage investigators also noticed an increase in bacterial numbers in sand filters after disinfection.

That heating soils increases their productivity has also long been known. Although the effect of heat may partly be accounted for on the assumption that heating alters the physico-chemical properties of soils, in such a way that the production of plant

* A full account of the Rothamsted work is given by Russell in his book 'Soil conditions and plant growth'. (64.) The whole subject of soil protozoa investigations is reviewed in a lengthy article in *Soil Science*, 171, 1911. pp. 197-269, by Kopeloff and Coleman

nutrients is accelerated, it undoubtedly also exercises some effect on the micro-organic flora and fauna. Russell and his collaborators have investigated the problem, and have shown that partial sterilization of certain soils by heat or by antiseptics causes a fall and then a rise in bacterial numbers, the latter change being accompanied by an increase in ammonification.

The evidence accumulated was interpreted as furnishing proof that these and other results are due to the existence in certain soils of some limiting factor, which is of the nature of living organisms, and which is probably protozoan. At first no direct evidence of the actual occurrence of protozoa in soils was forthcoming, but recently several investigators have identified definite species of protozoa in certain soils in many parts of the world.

Soil protozoa apparently possess the power of ingesting certain bacteria, including the beneficial bacteria present in soils, and in this way their occurrence to excess in certain soils may be highly detrimental.

Soil protozoa can easily be destroyed by partial sterilization by the use of anticeptics, or by heating. Thus sick greenhouse soils have been improved by heating the soils by means of steam pipes. Certain soils are apparently improved by partial sterilization brought about by the application of quicklime [40]. Loew has described the sick soils of Porto Rico [44], and, as the result of numerous experiments, has come to the conclusion that the infertility of these soils is largely due to the presence in them of an undesirable micro-organic population. He recommended the use of carbon bisulphide as an ameliorator, but pointed out that if the soils be properly aerated and exposed to the germicidal effect of the sun's rays by deep ploughing, the same result would probably follow. It is worthy of note that the sick soils referred to by Loew are red clay soils possessing a marked acid reaction. On the whole, there appears to be no very direct evidence that soil protozoa play an important rôle as a factor limiting plant growth in normal well aerated soils. Possibly, in certain badly ventilated sour soils, such as the so-called sick soils of greenhouses, the presence of protozoa may be in part responsible for lack of fertility. Proper aeration, accompanied when needed by liming, will in most cases probably bring about a suppression of the undesirable micro-organic life concurrently with the destruction of harmful organic toxic substances, and a general improvement in the physico-chemical soil conditions.

Bad aeration may inhibit the activities of beneficial micro-organisms in the soil, apart from the encouragement it gives to the development of their protozoan enemies. Since nitrification is the result of an oxidation reaction, it is undoubtedly affected by aeration as well as by acidity. Thus Schlösing [45] in 1868 noted that there was a rapid loss of nitrates when a moist humic soil was kept in an atmosphere of nitrogen. Warington in 1886 found that saturating a normal soil with water caused it rapidly to lose the nitrates it contained. Kelley [41] showed also that flooded rice fields contain little or no nitrates. Possibly these results may in part have been accounted for by the activities of bacteria of denitrification. These live under anaerobic conditions,

and have been shown to reduce nitrates in water-logged soils to nitrites and gaseous nitrogen (see Russell, 61, p 131).

3. METHODS OF DETECTING AND OF ESTIMATING OXIDATIVE ACTIVITY IN SOILS.

It has long been known that during the oxidation of organic substances in soils, oxygen is absorbed and carbon dioxide is evolved. The earlier workers believed that oxidation in soils was entirely controlled by micro-organisms. Several points of similarity were noted between soil oxidation and bacterial activity, such as, for instance, the effect of heat on the two processes.

(a) Russell [63] in 1905 studied oxidation by estimating the oxygen absorbed by soils. He found that the same factors which influence fertility also influence the rate of oxidation, and apparently to the same extent. The relative fertility of different arable soils of the same type may be approximately estimated by comparing their rates of oxidation. Russell concluded that the amount of oxygen absorbed by soils measures the total micro-organic action, which, by producing enzymes, hastens decomposition. He proved that the quantity of carbon dioxide evolved is not necessarily proportional to the quantity of oxygen absorbed during oxidation in soils, for many soils have a great power of absorbing carbon dioxide.

Russell's method of estimating oxidative activity in soils by measuring the amount of oxygen absorbed, is difficult and tedious to carry out, and is open to the objection that it takes no account of the respiratory needs of the micro-organic flora and fauna of the soil.

(b) A better method, which to the knowledge of the writer has never yet been employed in soil studies, would appear to be some modification of Bunzel's method.* This method is largely used by plant physiologists for measuring oxidase activity in plant saps. It depends on the fact that the rate of oxidation of pyrogallol by the oxygen of the atmosphere is accelerated by the presence of an oxidase in it. A special form of reaction flask is used. This is fitted with a manometer by means of which the decrease in pressure of its gaseous contents caused by the absorption of oxygen during the reaction can accurately be measured. For soil work, some modification in the design of the reaction flask would have to be made, but even then the method would be open to the objection raised in connection with Russell's method, namely that it takes no account of the respiration of the micro-organisms in the soil.

Schreiner and Sullivan [68] recommended the use of certain easily oxidized organic compounds which yield highly coloured products when brought into contact with oxidizing agents. They found an aqueous solution of aloin of 0·125 per cent. strength to give the best results. Twenty grams of soil are

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* See Atkin's 'Some recent researches in Plant Physiology,' p. 241—8 London, Macmillan, 1916.

shaken four or five times with 50 c. c. of the solution during the course of an hour, and then allowed to settle. If the solution is turbid, 50 c. c. of 95 per cent. alcohol are added to flocculate the soil and to extract the reagent. The mixture is then centrifuged, the supernatant liquid poured off, and the depth of colour in the solution compared with some standard in a colorimeter.

Besides aloin, gum guiacum, pyrogallol, hydroquinone, Alpha napthylamine and benzidine may be used to indicate or to estimate the oxidizing power of a soil.

(d) One of the most general and delicate reagents for recognizing the oxidizing property is hydriodic acid. This reagent has long been used in chemistry. Gerretsen [49] has used it with success in an examination of the sugar-cane soils of Java. An acidified 1 per cent. solution of potassium iodide is left for five minutes in contact with 2 grams of soil which is then quickly separated by centrifugation. The amount of iodine set free is estimated by a centinormal solution of sodium hyposulphite. The oxidizing power of the soil is expressed in miligrams of iodine per 100 grams of soil.

Gillespie [27] has recently drawn attention to the fact that oxidation in soils is the converse of reduction, and that a sharp line can be drawn theoretically between the two processes, taking as standard, the properties of pure water. This conception is an exact parellelism with the idea of acidity and alkalinity ; and just as in the latter case acidity is purely a relative term, so also is oxidation. Further, it has been shown that a neutral reaction is not necessarily the optimum condition for soils, but that a slightly acid reaction is more desirable. It is similarly true that the theoretical point between oxidation and reduction is probably not the best condition for soils. Differences in acid intensity have been studied in soils by electrometric potentiometer methods, and Gillespie proposes a similar method for estimating the reduction potential of bacterial cultures and soils. In this way he has furnished the soil chemist with a method of measuring the intensity of oxidation in a soil as contrasted with the total quantity of oxidation as estimated by former methods such as those already described.

Gillespie, in discussing the question of acidity in soils, expresses doubt as to whether the injurious effects of poor drainage on vegetation are due entirely to the high degree of acidity usually exhibited by badly drained soils. It would appear more likely that they are due to their high reducing power, which means the absence of adequate oxidation, and the consequent accumulation of organic toxins, or of ferrous compounds in such soils. Gillespie's investigations have shown that bacterial cultures are normally reducing, and it would appear to follow that the reducing power of water-logged soils may be due to the effect of bacterial activity, irrespective and independent of the chemical reactions involved in producing the reduction potential.

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STUDIES IN WEST INDIAN SOILS.

I. THE SOILS OF DOMINICA, THEIR GENESIS AND FERTILITY CONSIDERED IN RELATION TO REACTION.*

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INTRODUCTORY.

PART I. THE GENESIS OF THE SOILS OF DOMINICA.

(A) The Main Geological features of Dominica.

(B) The Origin of the Soils of Dominica.

1. The weathering of rocks.
2. The mineralogical composition of the volcanic rocks of Dominica.
3. The weathering of the more important minerals present in the volcanic rocks of Dominica.
4. The chief soil types of Dominica, and the factors responsible for their differentiation.

PART II. THE REACTION OF THE SOIL TYPES OF DOMINICA.

(A) The Data bearing on the subject.

(B) Discussion of the Data.

1. Soils of the Central Uplands.
2. Soils of the Windward Coastal Belt.
3. Soils of the Leeward Coastal Belt.

PART III. THE CORRELATION OF REACTION AND FERTILITY IN CERTAIN CACAO AND LIME SOILS OF DOMINICA.

(A) The Experiment Plots at the Botanic Station.

1. The Cacao Plots.
2. The Lime Plots.

(B) Other Leeward Coastal Districts, where cacao and limes are grown.

(C) The Upland Districts.

SUMMARY.

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INTRODUCTORY.

During a visit to Dominica extending from October 29 to December 6, 1920, the writer made a preliminary investigation into certain problems connected with the soils of that island, the results of which are set out in the following pages.

Recently the particular question of soil acidity has received some attention from various workers in the West Indies, notably in Antigua, St. Kitts and Dominica, and the data obtained in these investigations have been brought together in a paper by Sir Francis Watts, published in 1917 in the *West Indian Bulletin*[24].* The writer of that paper comments on the fact that, whereas certain West Indian soils growing such crops as sugar-cane, cacao and limes, regularly give satisfactory yields, and appear to be quite capable of supporting healthy and vigorous plants, yet many of them exhibit large lime requirements, and, according to the usual interpretation of this property, are to be classed as acid soils.

The term *acidity*, as used in its application to soils, possesses a meaning which has rarely been clearly defined in the past by agronomists. In order to obtain a clear understanding as to the meaning of soil acidity, the writer has attempted in another paper to summarize the results of recent investigations in this field of soil science, and to discuss the various factors which are responsible for the well-known characteristics of so-called acid soils. It is stated in that article that soil acidity, by its chemical definition as that condition of a soil which is due to the presence of excess of hydrogen-ions in the soil solution, is actually only one part of a broader conception to which the term *soil sourness* may be applied.

Sour soils present to plants many features not possessed by normal soils. These features, and the factors responsible for them, have been described in some detail in the article mentioned, and need only be summarily reconsidered here. Soils whose soil solutions contain an excess of hydrogen-ions, usually show, in addition, a deficiency in calcium. In many cases also, they contain excessive amounts of soluble toxic organic and inorganic compounds, such as salts of aluminium, iron and manganese. Finally, certain sour soils may contain an undesirable type of micro-organic fauna and flora.

The lime requirement of a soil which has often been proposed as a means of measuring soil acidity, does not give a true estimate of the *degree* of acidity. It may give some indication of the *quantity* of acid which may become reactive under certain conditions, and in a certain length of time, but it may also coincidently take some account of certain of the other factors above-mentioned. Part of the lime, for instance, may be removed in combining with toxic inorganic substances, or may be in part absorbed in producing those physical effects which are so frequently consequent on the liming of soils of poor tilth.

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* Reference is made by number to the bibliography tabulated in the appendix.

The occurrence of a considerable concentration of hydrogen-ion in a soil solution, unless present in high degree, is not in itself considered necessarily detrimental to plant growth. Indeed, many soil processes correlated with satisfactory plant growth, may best proceed in a medium of slightly acid reaction. It is only when the reaction of the soil solution is more acid than a reaction expressed by the pH value 5 *, that plant growth, at least for the majority of cultivated plants, may definitely be expected to suffer. In most sour soils it is the factors other than the presence of free acid that are probably responsible for infertiliyt. Frequently the lack of calcium compounds is the limiting factor for plant growth. In certain cases it is the presence of toxic amounts of aluminium, etc. In badly drained soils it is usually the lack of proper aeration which makes possible the accumulation of organic toxins, and the development of an undesirable micro organic flora and fauna. Hence in examining the cause of infertility of sour soils which possess a markedly acid reaction, not only the hydrogen-ion concentration must be determined, but also the degree to which these other inhibitors of plant growth exercise their effect should be estimated.

It was with the primary object of finding how far the acidity of certain soils growing cacao and limes in Dominica could be correlated with their productivity, that the present investigation was undertaken. The recent elaboration by certain American scientists of quick methods for determining the hydrogen-ion concentration of soils, has made it possible to study the acidity factor more or less independently of the other factors. This has been attempted by the writer for a limited number of examples of the soil types occurring in Dominica.

The calcium carbonate content of soils is intimately bound up with the intensity of acidity of the soil solution, since calcium carbonate functions as a base when in contact with water. It also plays an important part in supplying plants with the necessary amount of calcium for the requirements of their metabolism and further, its presence in the soil solution appears to be essential to the maintenence of a proper balance of nutrients. Hence any soil investigation connected with questions of fertility should include determinations of the total amount of calcium, and of calcium carbonate in the soils examined. The writer has estimated the calcium carbonate content of several of the soils in Dominica, and has used the results, together with those obtained by other investigators, in an attempt to explain certain problems connected with Dominican soils. He wishes to acknowledge the great assistance afforded him by the published records of work already performed in Dominica, and especially the report on the soils of that island drawn up in 1902 by the Hon. (now Sir) Francis Watts. [22]

The plan of the following presentation is first to deal with the genesis of the soils of Dominica. This involves summary

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* Gillespie and Hurst. *Soil Science*, VI, 1918, p. 235.

consideration of the main geological features of the island, especially as regards the mineralogy and chemical composition of its rocks, together with a brief discussion of the main factors that have produced from these rocks the various types of soil at present existing in Dominica.

The second part of the paper is concerned with the reaction of the different soil types. In it are stated the collected experimental data which may be taken to indicate the condition of the soils as regards sourness or otherwise. These data are discussed in an attempt to decide which of the main factors most generally responsible for acidity in soils have been influential in impressing an acid reaction on those soils of Dominica that have been found to be sour.

The third part deals with certain definite areas where cacao and lime trees are growing, and where the effect of various growth factors on the cacao and lime plants can be most satisfactorily studied. Especial attention is given therein to the experimental plots at the Roseau Botanic Station.

Finally, the interesting case of the upland soils of Dominica that support a luxuriant forest flora receives special consideration in respect of the fertility of those soils, and the question of their value in the event of possible extensive development.

The writer desires to make it clear that this paper is chiefly intended to form the basis of future detailed work, the necessity for which will become evident when its scope has been examined. Numerous problems connected with the fertility of the soils of Dominica suggest themselves, and, since many of these problems are presented also by the soils of certain others of the West Indian islands, it was thought advisable to discuss the subject of soil genesis of a typical area of high rainfall in its broadest aspect, as a preliminary to more detailed research.

It is a privilege to be able to acknowledge the great assistance afforded the writer by the Curator of the Botanic Station (Mr. Joseph Jones), and by the Assistant Curator (Mr. Alfred Keys), whose aid in securing the soil samples was invaluable.

PART I. THE GENESIS OF THE SOILS OF DOMINICA.

(A) The Main Geological Features of Dominica.

Very little is known of the detailed geology of Dominica. Apparently only two original papers having direct bearing on the subject have so far been published [14,16].

Dominica is the most mountainous of the Antillean islands, both as regards the actual elevation of its highest parts, which reach a height of about 5,000 feet at Morne Diablotin, and the ruggedness and inaccessibility of its uplands. The central part of the island consists of a more or less continuous range of mountains, which runs north and south and gives off spurs to the sea. The valleys are numerous, and usually very deep and narrow. Cultivation is practically confined to the lower grounds near the sea, and to the valley bottoms and the basal parts of the steep slopes that border them. The interior is for the

most part covered with dense tropical forest, excepting in one or two districts, as for instance, the area of Crown Land opened up by the Imperial Road in the centre of the island. In these districts deforestation has been practised with a view to reclaiming the land for arboriculture.

The geological structure of Dominica is mainly volcanic. Exposures of rock in sea-cliff or river sections and in occasional excavations in the interior, indicate that fragmental ejecta, such as volcanic dust, ash and stones, together with a smaller proportion of lava, make up the bulk of the island. Extensive erosion caused by intense weathering and rapid transportation by running water has greatly obliterated the original forms of the once active volcanoes. The age of the oldest volcanic rocks is, geologically speaking, recent. They were possibly extruded in the Pleistocene era, since which period vulcanicity has frequently recurred in Dominica. The latest eruption took place in 1880 at the Grande Soufrière in the south-east of the island. The island still shows abundant solfataric action, and a boiling lake is one of its interesting features. These and other natural phenomena indicate the geological youth of Dominica.

Spencer[16] divides the rocks of Dominica into the following systems. :—

1. Basement of older volcanic rocks.

   These consist of lava flows (formed almost entirely of andesite, with possibly a few minor flows of more basic rocks) with massive compacted tuffs (ash beds) and breccias (beds of cemented angular rock fragments) overlying them. The basement rocks are exposed in the interior, but most of the high ground above 1,500 feet consists of *newer* volcanic accumulations.

2. Roseau tuffs.

   Beds of fine-grained material with occasional gravelly layers fill an old valley which occupied the site of the present Roseau River.

3. Gravel formations.

   True water-worn gravels occur at the Grand Savanna and at Morne Daniel on the leeward coast. They were probably accumulated as an ancient sea beach.

4. Coral beds.

   These occur on the surface of the gravels at Morne Daniel near Canefield estate, at a height of some 50 feet above the present sea level, and also to a lesser extent near Roseau, as for instance at Morne Bruce, at about 150 feet above sea-level.

The presence of beach gravels and coral beds, as well as many of the surface features of Dominica furnishes evidence of recent uplift, which has been accompanied by increased river erosion.

(B) The Origin of the Soils of Dominica.

1. The Weathering of Rocks.

The basis of most soils consists of the mineral fragments derived from pre-existing rock masses by processes of disintegra-

tion and weathering. The type of soil which accumulates over any particular area depends on many factors, of which climate and the composition of the original rock which gave rise to the soil, are the chief.*

Climate largely determines the kind of weathering to which exposed rocks are subjected. In tropical countries weathering is mainly brought about by the agency of water, which acts both mechanically and chemically on rocks. Mechanically, it disintegrates rock masses by forcefully impinging upon them as rain. Chemically, it brings about their comminution by dissolving away material which cements the more resistant grains, or by reacting with certain easily decomposed minerals of which the rocks are constituted so as to give rise to soft, amorphous products. Thus the various forms of felspar which are present in high proportion in most igneous rocks are hydrolyzed by water to form kaolinite, a white, friable, clayey substance, and certain more or less soluble compounds, such as silica and compounds of the alkali metals. The chemical activity of water is greatly enhanced by the presence of dissolved oxygen and carbon dioxide in it. Such natural water is capable not only of causing the hydrolysis of certain minerals, but also of bringing about the oxidation of iron compounds frequently present in them, and of acting upon and dissolving various forms of calcium carbonate. In the tropics, these effects are greatly accelerated by the high temperature which prevails.

The products of weathering of rocks either remain *in situ*, and there give rise to soils, or are carried away by agents of transport, such as wind and running water, and deposited in some region more or less remote from the place where they were originally formed. Thus we have sedentary soils and transported soils. In the tropics, running water is in general the most important agent of transport. It rapidly removes weathered material from exposed rock surfaces, especially on steeply sloping ground. Frequently, however, the presence of a dense covering of vegetation on a weathered rock surface almost entirely prevents transport by running water, but it is evident that unusually heavy or long-continued rainfall must have an effect in removing the finely divided material in all regions, except perhaps, in perfectly flat districts. The sudden downpours known as cloud bursts, in which a great volume of rain is concentrated into a small area for a short space of time, sometimes produce disastrous results, removing all the loose soil and subsoil down to the solid rock below.

In Dominica the effects of weathering and of transportation are well defined. It is important that they should receive attention if one wishes to understand the origin and chemical nature of the various soil types that occur in the island. At the outset, the mineralogical composition of the underlying rocks should be noted.

*For a full description of the processes whereby rocks give rise to soils, the reader is referred to Rastall's, 'Agricultural Geology' *Cambridge University Press*, 1916.

2. THE MINERALOGICAL COMPOSITION OF THE VOLCANIC ROCKS OF DOMINICA.

Geological exploration in Dominica, as far as the writer is aware, has failed to reveal the presence of igneous rocks other than those belonging to the intermediate class of volcanic (or extruded) rocks, which includes the andesites and their fragmental equivalents (tuffs and breccias) that are produced by the explosive disruption of molten andesite during volcanic activity.* Possibly some more basic rock also occurs in Dominica, but this is of small account, and may be ignored in the general problem. The same type of igneous rock occurs in certain other West Indian islands, and during the outbursts in Martinique and St. Vincent in 1902, the products erupted in each case were closely similar in composition. The chain of West Indian islands indeed appears to be a branch of the Andean system of volcanoes, which coincides with a series of great parallel earth folds extending from South America to Mexico [7]. It has been pointed out by Iddings [8] that the volcanic rocks from this belt contain a preponderance of andesites and closely related rock types.

Andesite is a blue-grey, compact, finely-crystalline rock consisting of a definite assemblage of minerals, of which white glassy plagioclase felspar, and some dark-coloured ferro-magnesian mineral or minerals are the chief. Along with these, certain accessory minerals such as magnetite, apatite, olivine, etc. usually occur in small amount. According to the nature of the ferro-magnesian constituent, andesites are subdivided into hornblende-andesite biotite-andesite, augite-andesite, and hypersthene-andesite. The andesites of Dominica apparently belong to the last-named class.

An examination of the mineral fragments derived from the volcanic rocks of Dominica during the process of soil formation has been made by Watts, who identified the following minerals in them[22]: plagioclase felspars (labradorite and anorthite chiefly), hypersthene, augite, hornblende, magnetite, epidote, quartz, nepheline, and natrolite. Much non-crystalline glassy material is also present. Of these minerals, the felspars and the three ferro-magnesian minerals together with magnetite, and possibly also nepheline, were doubtless originally present in the volcanic rocks from which the soils were formed. There is no mention of the occurrence of apatite, the only phosphatic mineral present in igneous rocks. The Dominican soils, as indicated by their analyses, contain an appreciable amount of phosphate, so that the original rock must have contained a certain proportion of apatite. Possibly it was confused in part with nepheline in the microscopic examination, for the two are very similar in optical properties.

Furthermore, the analyses show that potash occurs in noteworthy amounts in the soils although potassium-bearing minerals are rare in rocks of the andesite class, and are conspicuously

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*For an account of the classification of igneous rocks, the reader is referred to Hatch's 'Textbook of Petrology' London. *Swan Sonnenschein & Co.* 1918; and to Harker's 'Petrology for Students' *Cambridge Univ. Press*, 1920.

absent from the list of minerals identified in the Dominican soils. We are bound to conclude that the potassium supply in the andesite is located in the glassy non-crystalline fragments, whose nature and composition can not usually be determined by a mineralogical examination. This conclusion is in full accord with the composition of the volcanic ash thrown out in the St. Vincent eruption of 1902,* for actually in this ash, most of the potash was found to occur in the glassy particles.

Epidote, quartz, and natrolite (a zeolitic mineral) probably represent decomposition products of certain of the original rock minerals, for they are amongst the common secondary products produced by weathering of felspars and ferro-magnesian minerals.

3. THE WEATHERING OF THE MORE IMPORTANT MINERALS PRESENT IN THE VOLCANIC ROCKS OF DOMINICA.

i. *Plagioclase felspars.* The minerals of this group are double silicates of sodium or calcium and aluminium. Albite (soda felspar) has the formula $Na_2O \cdot Al_2O_3 \cdot 6SiO_2$. and anorthite (lime felspar) $CaO \cdot Al_2O_3 \cdot 2SiO_2$. Labradorite (lime-soda felspar) and andesine (soda-lime felspar) are isomorphous mixtures of these two extreme types. During weathering, the felspars are hydrolysed and yield kaolinite plus silica, and either sodium or calcium hydroxide or both, depending on the nature of the original felspar. e.g. (a): $Na_2O \cdot Al_2O_3 \cdot 6SiO_2 + 3\ H_2O = Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O + 4\ SiO_2 + 2KOH$.

(b) $CaO \cdot Al_2O_3 \cdot 2\ SiO_2 + 3\ H_2O = Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O + Ca(OH)_2$.

Kaolinite is a white substance which, in its purest form, constitutes china clay. Silica, when it forms one of the products of hydrolysis, usually combines with the alkaline hydroxide also liberated to form a silicate, which, being soluble, is removed in solution. Or the hydroxide may react with carbon dioxide in natural water to form a soluble carbonate or bicarbonate. Thus the lime-bearing felspars yield calcium bicarbonate as a soluble product of weathering. The great importance of this result will be discussed later. Actually the weathering of the plagioclase felspars is not so simple as outlined above. Lime felspars, for instance, in the presence of ferro-magnesian minerals, often give chlorite or epidote as intermediate products. Both these minerals occur in the Dominican soils.

In tropical countries, under certain conditions not yet fully understood, felspars give rise, not to silicates as previously described, but to various hydroxides of aluminium, the most important of which are gibbsite ($Al_2O_3 \cdot 3H_2O$), bauxite ($Al_2O_3 \cdot 2H_2O$), and diaspore ($Al_2O_3 \cdot H_2O$). All the bases and the greater part of the silica originally present in the felspars have been leached out and removed in solution. Weathering of this type is known as *lateritization*, and there are evidences of its incidence in certain parts of Dominica, especially in the wet upland regions. Prof J. B. Harrison has described the lateritization of fel-

* See *Agricultural News*, I, 1902, p. 89.

spar of certain basic and intermediate rocks in British Guiana[9]. It is possible that the process is very common in many of the wetter West Indian islands where igneous rocks occur. It is of economic interest, in that it gives rise to workable raw materials (bauxite and gibbsite), which are largely used in the electrolyte manufacture of metallic aluminium.

ii. *Ferro-magnesian minerals.* Hypersthene is a double silicate of iron and magnesium. Augite and hornblende are double silicates of calcium, iron, and magnesium chiefly. During weathering, these minerals are converted into various silicates, such as epidote, chlorite and serpentine, often with separation of iron in the form of oxides or hydroxides (magnetite, haematite, limonite), together with carbonates and other compounds of very uncertain character and composition. Under conditions favourable to lateritization, as described in the last section, the sole insoluble product may be a mixture of aluminium hydroxide and ferric hydroxide of a bright-red colour; the calcium and magnesium compounds and the silica having been more or less completely removed by leaching.

4. THE CHIEF SOIL TYPES OF DOMINICA AND THE FACTORS RESPONSIBLE FOR THEIR DIFFERENTIATION.

In order to obtain some idea of the differences that are likely to exist between the soils occurring in the various topographical regions of Dominica, a consideration of the main factors that are responsible for the differentiation of soil types of the same geological origin would appear to form a logical introduction to the discussion.

The topography of a country largely decides the climate of its various parts. Mountainous districts usually have the highest rainfall. In insular countries, the windward side is usually more rainy than the leeward, except in those islands where the surface of the land is lowlying or only slightly elevated. In Dominica the distribution of the rainfall, as indicated by meteorological observations recorded at several stations,* permits of the subdivision of the island into three main regions, which may be designated and described as follows:—

1. The *central uplands* of elevation 1,000 feet up to 5,000 feet, and of mean annual rainfall of about 180 inches (variation 150 to 300 inches).
2. The *windward coastal belt*, including the north and the south coasts, from near Blenheim to near point Mulâtre, of mean annual rainfall of about 135 inches (variation 100 to 150 inches).
3. The *leeward coastal belt*, including the extreme north and south coasts of the island, and of mean annual rainfall of about 86 inches (variation 60 to 100 inches).

There is a fairly distinct alternation of dry and wet seasons in all these three regions, the former period extending from

* Annual Reports of the Dominica Botanic Station, 1909-19.

January to May, and the latter from June to December. The change from the wet season to the dry is occasioned by the setting in of the north-east trade wind, which blows with great regularity during the earlier months of the year, and prevents in some measure the formation of rain clouds.

A study of the geographical distribution of soil types over large areas of approximately uniform geological strata, such as exist in Russia, Germany and America, has shown that the dominant controlling factor is climatic rather than geological. Further, it has been demonstrated that rainfall is the climatic condition that is most potent in this connexion, temperature appearing to be of secondary importance *. In areas of comparatively small size, the effect of rainfall in deciding the ultimate composition and properties of soils is also of some moment. Its influence on the soils of such an area as Great Britain, where the variation in rainfall is only small, has been clearly indicated by soil surveys. We are justified, therefore, in expecting that the soils of Dominica might show appreciable differences when representative samples from the three climatic regions of the island are compared in detail. A study of the results of the analyses of typical Dominican soils, as presented in the Report previously alluded to[22] and summarized in the following table, indicates that this conclusion is fully warranted. Such a study enables one to form a fairly accurate estimate of the processes which have given rise to the soils that now exist in the three main climatic regions of Dominica.

The soil samples examined by Watts were twenty-three in number. They were taken from twenty estates or districts, which are divided between the three climatic regions as follows (see appended map) : –

1. *Central Uplands.* Middleham, Sylvania, Corona, Riversdale, Bona Vista, and Amelia.
2. *Windward Coastal belt* (including also the north and the south coasts). Blenheim, Hampstead, Melleville Hall, Castle Bruce, and Rosalie.
3. *Leeward Coastal belt.* Point Mulâtre, (South Chiltern),† Geneva, Roseau Botanic Station, (St. Aroment),† (La Haut),† Clarke Hall, Hatton Hall (now known as Picard), and Moore Park.

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* Rastall : ' Agricultural Geology ', p. 162.

†The districts named in brackets are not typical of the last region, as they are situated on elevated land of higher rainfall than that which is representative of the region.

TABLE I.

Chemical Composition of 20 per cent. Hydrochloric acid extract of Soil, expressed as Percentage of Dry Soil.

	Six Central Upland Estates.		Five Windward Coast Estates.		Six Leeward Coast Estates.		Typical laterite soil, Madras, India.
	Mean value.	Limits of variation.	Mean value.	Limits of variation.	Mean value.	Limits of variation.	
Insoluble residue ...	51·10	±9·35	59·90	±10·39	71·37	±8·56	76·86
Soluble silica ...	0·27	±0·22	0·38	± 0·19	0·11	±0·04	—
Alumina (Al_2O_3) ...	9·40	±4·17	11·11	± 3·75	6·18	±3·09	8 81
Ferric oxide (Fe_2O_3)	10·23	±5·06	10·68	± 2·84	8 83	±4 36	10·09
Manganese oxide (MnO)	0·59	±0·50	0·45	± 0·43	0·05	±0 04	—
Lime (CaO)... ...	0·37	±0·18	0·33	± 0·26	1·34	±0·61	trace
Magnesia (MgO) ...	0·09	±0·08	0·08	± 0·05	0·24	±0·19	0·77
Potash (K_2O) ...	0·10	±0·03	0·08	± 0·02	0·10	±0·04	0·00
Soda (Na_2O) ...	0·17	±0·15	0·26	± 0·19	0·42	±0·27	0·17
Chloride (Cl) ...	0·005	±0·004	0·01	± 0·006	0 01	±0·01	—
Sulphate (SO_4) ...	0·09	±0·09	0·05	± 0 06	0 07	±0·11	—
Phosphate (P_2O_5) ...	0·08	±0·06	0·09	± 0·05	0·10	±0·05	trace
Combined water ...	11·31	±5·23	7·88	± 2 14	5·16	±3·91	2·87
Humus	7·14	±5·77	2·25	± 0·79	2 36	±0·91	
Calcium carbonate	0·34	±0·18	0·15	± 0·14	0·28	±0·25	0·27

DISCUSSION OF THE TABULATED RESULTS (TABLE I).

(a) *Lateritization.*

The general chemical composition of the Dominican soils, considered as a whole, resembles markedly that of typical lateritic soils such as occur in India. In the table, an example* of a lateritic soil from Madras, India, is included for comparison. The high percentage of acid-soluble matter in the Dominican soils (which cannot be correlated with a high carbonate content since this is actually low in the soils), and the high percentage of combined water, especially in the upland soils are typical of lateritic soils, in which free aluminium hydroxides and iron hydroxide are present in abnormal proportions. The low percentage of soluble silica and of easily soluble bases is also typical of soils that have been exposed to continuous and excessive leaching action by water (see p. 91). The analytical figures show that the mean percentage of total acid-soluble matter, which includes the hydroxides of aluminium and iron hydroxides may be definitely correlated with the intensity of the rainfall, for in the leeward coast samples there is much more insoluble matter and considerably less aluminium and iron hydroxides than in the upland samples. Lateritization has apparently not gone on so completely in the drier regions as in those of high rainfall.

(b) *Leaching.*

The figures for the bases lime, magnesia, potash and soda show striking differences between the soils of the three climatic regions. It is usually assumed that 20 per cent. hydrochloric acid as employed in a soil analaysis, abstracts from soils amounts of these bases approximately proportional to the total quantities present, and more especially, that it completely decomposes all compounds of the alkali metals except the more stable complex silicates. The differences mentioned may now be interpreted as follows.

Of the bases lime, magnesia, potash and soda the first two are usually more readily leached out of soils than the last two. Thus in relation to leaching at Rothamsted, Russell writes :† ' As might be expected from the known absorbtive properties of clay and of humus, drainage water contains mere traces of NH_4 and PO_4 , and only little K ; it contains chiefly carbonic acid, SiO_3 , Cl, SO_4 , NO_3 , Ca, with some Fe, Mg and Na.' The wastage in drainage water at the same station was found, on the average, to be, per acre per annum: lime, 98 to 226 ℔.; magnesia, 5 to 20 ℔. and potash, 3 to 12 ℔.

An extensive series of experiments has been carried out at the Florida Agricultural Experiment Station (see *Bull* 132, Nov 1916) in order to test the loss of nutrient substances from soils by leaching. The results of five years' work indicate that, in so far as the conditions obtaining in Florida are concerned,

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*Quoted by Rastall ' Agricultural Geology ', p. 161.

† Russell : ' Soil conditions and plant growth ' London *Longman's Green*, 1917, p. 69.

newly cleared land, when exposed to heavy rainfall soon loses much of its fertility hrough leaching. Phosphoric acid and potash are lost in small amount, but lime was found to be lost in considerable quantity, and this rapid loss to result in an acid soil condition.

Although quantitative generalisations cannot be made for soils of widely separated regions, one is justified in stating that, in any soil exposed to leaching, lime is the base which, as calcium bicarbonate, is most readily removed by leaching, and that at the other extreme, potash is the base which is least easily removed.

Assuming then, that the rocks that have given rise to the soils of Dominica are of practically uniform chemical composition, we may explain the considerable excess of lime present in the low-level soils of the leeward coastal belt, as compared with the soils of the upland region, and with those of the rainy windward coast to the greater amount of leaching that has gone on in the two last-mentioned regions. The relative amounts of magnesia, soda and potash present in these three types of soil are in accord with this conclusion.

Furthermore, it is perhaps reasonable tc assume, that a certain amount of the easily-leached bases, especially lime, present in the water draining off the high land, has been held up in some way in the leeward coast soils, and has thus augmented the supply of lime, magnesia and soda in them. Such retention would be less likely to occur in the windward coast soils where rain is more frequent, and where most of the drainage water is quickly carried to sea.

In support of this last theory, the following analyses of the water * draining away from the uplands in certain of the rivers of Dominica are presented:—

Constituents expressed as parts per 100,000.	Water-supply, Roseau.	In take of Reservoir, Roseau Valley.	Sweet River, where it leaves the forest.	Soufrière water-supply.
Total solids	16·4	17·6	16·0	31·5
Temporary hardness (calcium and magnesium bicarbonates chiefly) ..	3·0	3·1	3·2	7·8
Permanent hardness ...	nil	nil	nil	2·8
Sodium chloride ...	2·6	2·3	2·1	7·1

* Tempany. Dominica Bot. Sta. Ann. Report, 1915-16, p. 40-41.

These analyses indicate that leaching is still in progress in Dominica, and that the surface and drainage waters from the heights are still bringing down considerable amounts of base, some of which, especially in the valleys, might reasonably be expected to be retained by the low-level soils of the drier regions.

In this connexion Hilgard's conclusions drawn from the published results of an exhaustive soil survey of Madagascar are worthy of note. Hilgard writes * " It is apparent that lime and potash are extremely deficient in the soils of the mountain slopes of central and southern Madagascar, these substances having, as elsewhere in the humid region, been leached down into the valleys'.

As a result of excessive leaching, one would expect to find the soils of very rainy upland districts less alkaline then those of drier lowland districts, for the rapid removal of bases from rocks undergoing weathering would tend to deprive them of the substances that are responsible for the alkaline reaction. How far these remarks apply to Dominican soils will be indicated in Part II of this paper.

(C) *The mode of occurrence of calcium in the soils of Dominica.*

The analyses indicate that, whereas the total lime in the soils of the leeward coastal belt is considerably greater than in the soils of the upland regions, the amount of calcium carbonate present in these leeward soils is less than that in the upland soils. This would appear to imply that the leeward lowland soils contain calcium combined in some easily decomposed compound other than the carbonate, and that the upland soils do not contain the compound in any appreciable quantity. The nature of the unknown calcium compound has not been definitely determined. It may possibly be calcium silicate or even calcium aluminate formed by interaction of free aluminium salts in the soil solution of the lowland soils with calcium bicarbonate brought down by leaching from the uplands. Only additional analytical work after the method used by Shorey, Fry and Hazen [15] for example, could definitely establish its identity.

PART II. THE REACTION OF THE SOIL-TYPES OF DOMINICA.

The significance of the reaction of soils in relation to the fertility of those soils, has been reviewed in the introductory. It now becomes necessary to consider the question of the reaction of the several soil types of Dominica as outlined in the last section, and to find how far this has been decided by the origin and mode of formation of these soils, and to what extent it is related to their fertility.

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* Hilgard. E. W. "Soils" New York. Macmillan Co. 1918. p. 407.

(A) The Data Bearing on the Subject.

Several soil samples† were obtained from various estates on the leeward coast and in the upland region. No samples from the windward coastal belt could be taken at the time; their detailed study will have to be deferred to a future occasion.

The reaction of the soil samples collected were quantitatively estimated by the use of Gillespie's colorimetric method for determining hydrogen-ion concentration as described at page of the writer's article on soil sourness[6]. A certain number of determinations of the calcium carbonate content of several of the soil samples was also made. Marr's modification of Amos' method* was used. Finally the samples were tested as to their deficiency or otherwise in easily-soluble bases by Comber's method.°

The results obtained in these experiments, together with a certain number of data recorded by other workers, are set out in the following two tables (Tables II and III).

In connection with the reaction of the Dominican soils, an attempt is made in Table IV to find how far the reactions exhibited by soil samples of the regions surveyed may be correlated with the hydrolytic ratios of those soils. By 'hydrolytic ratio' is meant the ratio of the percentage of acid-soluble calcium and magnesium oxides, to the percentage of acid-soluble aluminum, iron and manganese oxides. Spurway[17] in a study of certain glacial soils of Michigan, found that there existed a definite relationship between the hydrolytic ratios of these soils and their reaction to litmus. Soils with the lowest hydrolytic ratio were found to be the most acid. The writer has applied Spurway's method of treatment of analytical results to the figures obtained by Watts[22]. The results obtained are set down in Table IV.

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† The soil samples were taken with a soil auger. Six cores were obtained at properly spaced points and united to form one sample. The top soils were taken to a depth of 1 foot, and subsoils, where specified, between the first and second foot.

* Marr: *Journ. Agr. Sci.* II. 1909, p. 155; Amos: *ibid.* I. 1905, p 322.

° Comber's test (*Journ. Agr. Sci.*, X. 1920, p. 420) depends on the fact that soils deficient in easily-soluble bases exchange ferric-ion for potassium-ion when an alcoholic solution of potassium thiocyanate is mixed with them, the test solution becoming blood red in colour when there is a deficiency of base in the soil under examination.

1. Soils of the Central Upland Region.

TABLE II.

Soil.	District.	Description of Soil.	Rainfall in inches.	Hydrogen-ion concn ; pH. values.	Percentage of calcium carbonate.	Deficiency or excess of easily sol. base (Comber's test).
I.	Saltoun. (16 acre plot	Top soil silty and black to 4″, whitish clay below.	200	4·4	0·020	Marked deficiency.
II.	Saltoun. (9 acre plot)	Top soil silty and black to 12″, reddish clay below to 24″, then white clay.	200	4·6	0·103	Deficiency.
III.	Saltoun. (Virgin forest)	Top soil silty and black to 20″, reddish clay below.	200	4·7	0·107	Deficiency.
XI.	Brantridge. (No. 19 plot)	Top soil silty and black to 6″, red clay below to 24″, then white clay.	230	4·9	0·037	Marked deficiency.
IX	Wotten Waven.	Rocky hillslope ; sandy black soil.	170	5·1	–	Marked deficiency.
X.	Wotton Waven.	Flat land ; sandy black soil with reddish clay below.	170	5·1	0·097	Marked deficiency.

The lime requirements of seven typical interior soils were determined by G. A. Jones* who used Hutchinson-McLennan method.† The result vary from 0·4 to 0·8 parts of calcium carbonate required to "correct the acidity" of 100 parts of soil. Jones noted that the forest soils were 'very acid in nature, especially when drainage is deficient owing to the close proximity of hard pan (solid rock) to the surface.'

It is especially worthy of mention that the *subsoil*, corresponding to the top soils tabulated above, in each case

* Annual Rept. Dominica Bot. Sta., 1916-17, p. 32 ; also recorded by Watts (24).

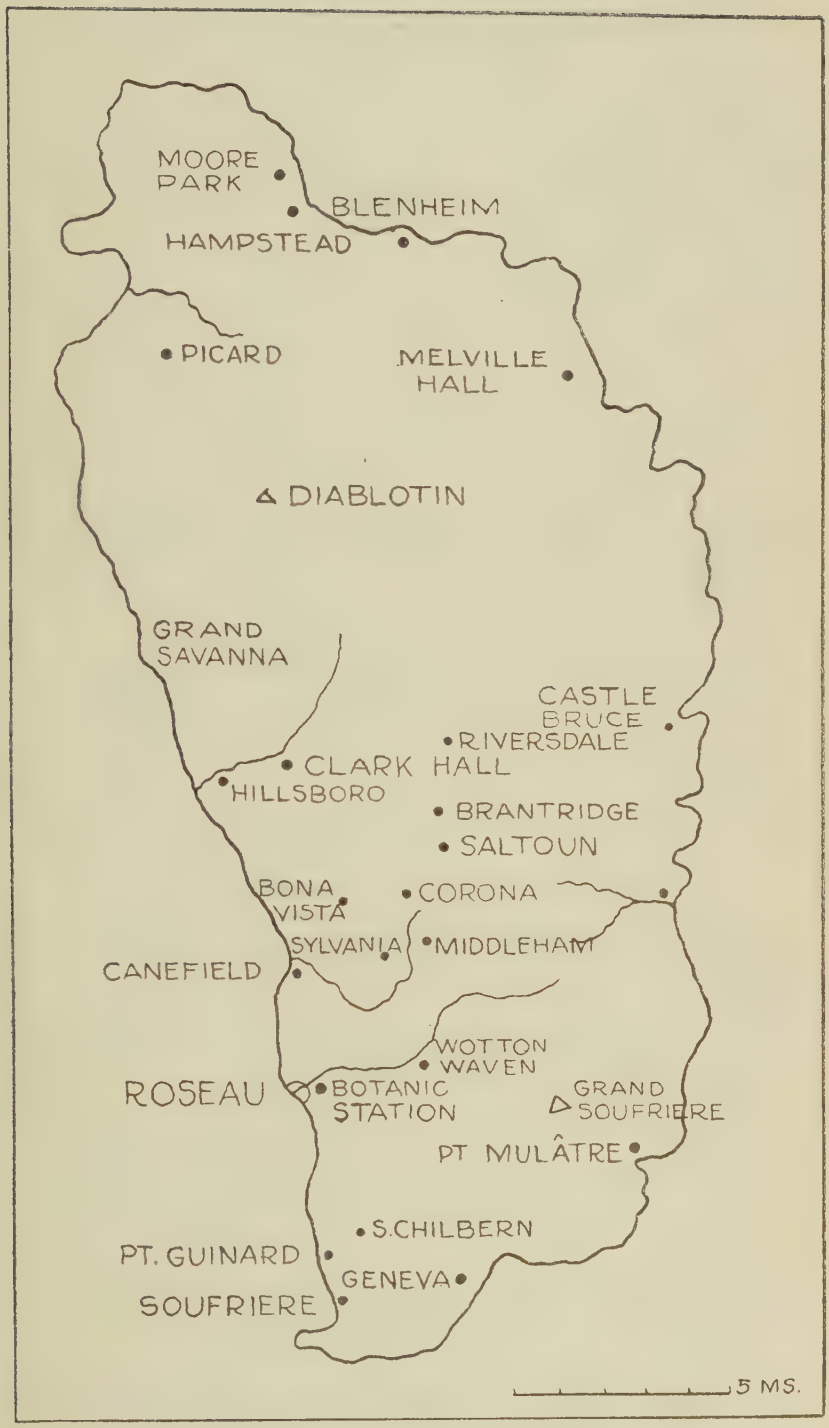
† *Journ. Ag. Sci.*, VII ,1915, p. 75.

gave a hydrogen-ion concentration (pH value) of the same number as that of the top soil, or differing from it by only 0·1. These results are, however, not recorded in the table.

3. Soils of the Leeward Coastal Belt.

TABLE III.

Soil.	District,	Description of Soil.	Rainfall in inches.	Hydrogen-ion concn; pH. values.	Percentage of calcium carbonate.	Deficiency or excess of easily sol. base (Comber's test).
	(*a*) *Hillside*	*soils.*				
XX.	Picard. (No. 13 plot)	Top soil clayey, subsoil reddish clay. Elevation about 500 feet.	90	5·1	–	Marked deficiency
XIX	Picard. (Blonchar)	Clay soil. Elevation about 800 feet.	100	5·6	–	Deficiency
XXII.	Soufriere.	Black sandy soil in pockets on stony hillside.	78	6·4	–	Neither
XII.	Pt. Guinard.	Ditto:	80	6·7	0·077	Excess
XVIII	Botanic Station. Lime plots.	Clayey soil receiving occasional mulch. Rocky hill slope.	80	6·8	–	Slight excess
XVI.	Canefield.	Top soil clayey and black to 8″. Red clay subsoil below.	74	7·0	0·037	Neither
XV.	Canefield.	Ditto:	74	7·4	–	Neither



SKETCH MAP OF DOMINICA.

3. Soils of the Leeward Coastal Belt.

TABLE III.—(*Concld.*)

Soil.	District.	Description of Soil.	Rainfall in inches.	Hydrogen-ion concn ; pH. values.	Percentage of calcium carbonate.	Deficiency or excess of easily sol. base (Comber's test).
	b) Valley soils.					
VI.	Clarke Hall.	Black silty alluvial soil.	100	6·4	0·030	Deficiency
IV.	Roseau, Bath.	Sandy soil on rocky flat near river.	80	6·5	–	Slight deficiency
XXI.	Soufriere.	Sandy black soil on stony flat land.	78	6·6	0·063	Neither
V.	Roseau. Bath near Emsall.	Sandy black soil on stony land at base of valley cliff.	80	6·7	0·080	Excess
VII.	Clarke Hall.	Black clayey alluvial soil with clay subsoil at 24 inches.	100	6 7	0·0043	Neither
XIV.	Canefield (Cacao bottom).	Sandy soil on recent alluvium.	74	6·8	0·023	Slight deficiency
XVII.	Picard.	Silty black soil with yellowish clay sul soil at 24″.	90	6·9	0·053	Slight deficiency
C	Botanic Station Cacao plots.	Sandy soil with gravelly subsoil.	78	7·0	0·081	Neither
VIII.	Hillsboro'.	Deep black silty soil of excellent tilth.	78	7·3	0·117	Considerable excess
XIII	Canefield.	Sandy soil on old alluvial flat. Stony subsoil.	74	7·9	0·160	Considerable excess

The lime requirements of a typical leeward coast soil (locality not stated) and of three soils of the Botanic Station were estimated by G A. Jones (*loc cit.*) The values are considerably lower than those obtained for the interior upland soils. They range between 0·025 and 0·175 parts of calcium carbonate per 100 parts of soil.

THE HYDROLYTIC RATIOS OF CERTAIN DOMINICAN SOILS.

TABLE IV.

Region of soil type.		$CaO + MgO$.	$Al_2O_3 + Fe_2O_3 + MnO$.	Hydrolytic Ratio. $\frac{CaO + MgO}{Al_2O_3 + Fe_2O_3 + MnO}$	Hydrogen-ion concn. pH values.
Central Uplands	Upper limit	0·30	23 19	1 : 77	
	Mean	*0·46*	*20·22*	*1 : 44*	4·8
	Lower limit	0·53	15·98	1 : 30	
Windward Coastal Belt	Upper limit	0·28	25·19	1 : 91	
	Mean	*0·41*	*22·24*	*1 : 54*	–
	Lower limit	0·84	22·97	1 : 27	
Leeward Coastal Belt	Upper limit	1·48	23·51	1 : 16	
	Mean	*1·58*	*15 06*	*1 : 9·5*	6·8
	Lower limit	2·41	10 64	1 : 4 5	

Note :—The hydrolytic ratios as set out in the above table are calculated from Watt's analytical data. The percentages of bases soluble in 20 per cent., hydrochloric acid were used in these calculations. Spurway (17) however used N/5 acid. The recorded pH values are the mean values of the results obtained by the writer for soils of the same regions as those dealt with by Watts, but the actual samples examined are not coincident therewith. Hence no exact correlation between the ratios and the pH mean values can be drawn. The pH figures are merely inserted to indicate the general agreement between the intensity of acidity of the soils of the three climatic regions as measured by the hydrolytic ratios and by the hydrogen-ion concentration.

(B) DISCUSSION OF THE DATA.

1. SOILS OF THE CENTRAL UPLAND REGION.

An inspection of the results set out in Table 11 indicates that the soils of the upland regions of high rainfall are markedly sour, for they all exhibit acid reactions towards indicators corresponding to a high concentration of hydrogen-ion ; are

notably deficient in easily-soluble bases ; contain low percentage amounts of carbonate, and have large lime-requirements. The hydrolytic ratios, as calculated from the composition of the acid extracts of the soils of this region, are characteristically high indicating also a markedly sour condition for these soils. Furthermore it is to be noted that the subsoils were found to be similar in reaction, and to possess in their soil solutions approximately the same hydrogen-ion concentration as the top soils corresponding to them.

There is evidently some potent acid-forming agent at work in these upland soils. The nature of soil acids in general has been described in the writer's article on soil sourness (6). It would appear from the list of acidic compounds tabulated at p. 45 of that article that in the the case of the upland soils of Dominica one would look for the acidic compound amongst the following substances.

(a) Alumino-silicic and silicic acids.

(b) Aluminium salts or salts of iron and manganese.

(c) Organic acids.

Only further detailed work could be hoped definitely to establish which of these is mainly responsible for the high, acidity of the upland soils.

A cursory inspection of the upland region would lead one to suppose that the almost permanently damp conditions that prevail there would be favourable to the accumulation in the soils of this region of organic waste products of an acid and toxic nature, and to suspect that oxidation is almost lacking in them. Although this may be true in many of the upland districts, especially in the clay-filled hollows, and in those places where sheet rock (locall known as hard-pan) immediately underlies the shallow surface soil, yet there are many localities where the natural drainage is fair. The mechanical soil-analyses reported by Watts [22] indicate that the majority of the upland soil samples examined by him were of a sandy or silty nature. One would expect such soils to occur on the sloping grounds of the uplands. The writer was able to confirm this by his own observations. Furthermore it was noted that the colour of the soil and subsoil in these better drained areas was of a bright red colour indicating that oxidation has gone on to a marked extent in them, for a red in soils is usually caused by the presence of iron in its most highly oxidized form.

There is one fact which is worthy of reiteration, in that it indicates the importance of mineral acids as distinct from purely organic acids as a major factor in deciding the reaction of many of the upland soils. It is the observation that, in all the soil samples examined, the subsoils exhibit the same degree of acidity as the top soils, and in some cases were even more acid than they. Specimens of pure red clay taken from a pit at a depth of four feet below ground level were also found to have as great intensity of acidity as the top soils, It is difficult to conceive how organic acids could be formed at these depths, or how they could penetrate so far below the soil surface so as to account for the acidity of these subsoils.

In conclusion it may tentatively be stated as a generalization that the main factor responsible for the acid reaction of the majority of the upland soils is either the presence of alumino-silicic acids or of hydrolizable salts of aluminium and iron. Possibly in the water-logged areas, where the soils are especially rich in humus washed down from surrounding sloping ground, the acidity may aiso in part be due to organic acids in the soil solution.

A detailed soil survey of the upland regions of Dominica would be necessary in order to establish the distribution of sour soils whose acdity is due to the various factors mentioned. Such a survey would appear to be the only method of defining the cause of sourness in any particular locality.

2. SOILS OF THE WINDWARD COASTAL BELT.

As has already been mentioned, the soils of this region have not as yet been examined as to the hydrogen-ion concentration of their soil solutions. The general chemical characteristics of the soils (tables I and IV) indicate, however, that they differ but little from the upland soils, and to some extent may be considered as being intermediate between these upland soils and the soils of the leeward coastal belt. They apparently show considerable variation amongst themselves, however, and a detailed investigation might lead to interesting revelations in connexion with their genesis and fertilty.

3. SOILS OF THE LEEWARD COASTAL BELT.

The experimental data set out in Table III indicate that the soils of leeward coastal belt of comparatively low rainfall are on the whole approximately neutral in reaction. Neutrality is represented by a pH value of 7·0, and the typical reaction of these soils lies between pH 6·4 and 7·4 having an average value of something near 6·8. The soils, however, do not contain appreciable excess of calcium carbonate. It must be borne in mind that the lowland soils are probably receiving constant additions of calcium carbonate leached out of the upland soils, and this may prevent their carbonate content from falling dangerously low. Apparently, from Comber's test, there is only in a few cases a deficiency of easily soluble base in these soils, and their lime requirements are either negative or low. The hydrolytic ratios of the leeward soils are very small, and in this characteristic they stand out in marked contrast to the soils of the other two climatic regions.

The data would appear to fall into two groups, and to indicate the subdivision of the leeward soils into hillside soils and valley soils. (Table III.) The former, on the whole, are more acidic in reaction and more deficient in easily-soluble bases than the latter. These differences may be assigned to the greater leaching action to which the hillside soils have been and are subjected.

PART III. THE CORRELATION OF REACTION AND FERTILITY IN CERTAIN CACAO AND LIME SOILS OF DOMINICA.

In order to find out how far the reaction of the Dominican soils growing cacao and lime trees can be correlated with the productivity of these soils, an investigation into the growth conditions presented by the experiment plots of the Roseau Botanic Station was undertaken. The results of this investigation are applied to other cases of cultivated soils of the leeward coastal region, to discover whether or no those relationships between reaction and fertility which apparently hold in the case of the Botanic Station plots, are capable of broader application in Dominica. A similar attempt is made in connection with the soils of the upland regions. The soils of the windward coastal belt were not studied.

It would be advisable to consider these various areas in the order indicated.

(A) The Experiment Plots of the Botanic Station.

The area occupied by the Dominica Botanic Station exists on the site of an old river bed or alluvial flat which is now elevated somewhat above the level of the present river owing possibly to earth uplift with which however, the river has kept pace by deepening its present valley.

The soil of the Station, especially along the base of Morns Bruce, is a sandy loam of an average depth of three or four feet.

On the whole, it does not differ greatly, at least as far as geological origin and mineralogical composition are concerned, from the soil of the neighbouring parts of the Roseau valley, of indeed from that of the lower parts of many similar valleys or the leeward coastal belt of Dominica.

1. The cacao plots.

The land set aside for the manurial experiments with cacao at the Botanic Station includes three main series of plots which have been laid down at various times. They may be described as follows.

(i) The *original series* of five plots (A to E) laid down in 1900 on land bearing cacao trees of age ten years.

(ii) The *additional series* of four plots arranged in two sets i. e.

(a) Plots F and G which form an extensive of the original series, and

(b) Plots H and I which are laid out on the steeep slopes of Morne Bruce bordering the last two plots.

These four plots were inaugurated in 1907.

(iii) The *new series* of two plots K and L, laid out in 1913, on the hillside in the vicinity of the plots H and L.

The hillside plots H, I, K and L were intended to test the effects of certain treatments found to be beneficial by the results

of the original series of trials, on cacao planted under conditions which are typical of much of the cacao land of Dominica.

The manurial treatments and the results obtained in the trials, together with the detailed history of the experiments, are, fully described and discussed in the Annual Reports of the Dominica Botanic Station and in various numbers of the *West Indian Bulletin*.[4], [2], [18]. The necessary details for the purpose of the present article are contained in the following table, (Table V.)

CACAO PLOTS.

Designation of plot.	Manurial treatment.	Average annual yield in lb. per acre of cured cocoa calculated up to 1920.	Percentage increase in yield over no manure plot.
(i) A.	Phosphate (basic slag and potash).	1430 lb.	25·3±2·5*
B.	Organic nitrogen (dried blood).	1396 lb.	22·3±2·6
C.	Control (no manure)	1141 lb.	——
D.	Vegetable mulch.	1763 lb.	54·5±1·6
E.	Complete manure.	1633 lb.	43·1±1·9
(ii) F.	Vegetable mulch.	2060 lb.	138·5±1·9
G.	Organic nitrogen (Cotton seed meal).	1653 lb.	91·4±1·2
H.	Control (no manure)	863 lb.	——
I.	Vegetable mulch.	1558 lb.	80·0±1·9
(iii) K.	Vegetable mulch + Lime.	1003 lb	16·2
L.	Nitrolim replaced, after one year by cotton seed meal.	1280 lb.	48·3

The physical properties of the soils of the different plots have been described by Tempany[18] as follows. 'The soil of the plots A to G is of a distinctly light and sandy nature but tends to become heavy on plots D and E which are at a slightly lower level than the other plots. The soil of the hillside plots is similar in texture to that of D and E. The subsoil forms a continuation of the top soils and presents a considerable thickness of coarse sands and gravels through which water percolates freely. During the rainy season the water-table usually stands about eight feet below the surface of the ground; . . . . . the subsoil water supply is augmented by drainage from the slopes of Morne Bruce." (ibid p. 84).

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* The probable errors given in this column are those calculated by Tempany. ([18].) The yield figures have been criticised by Dunlop ([14]) and defended by Jones ([12].) Probably the percentage increases as tabulated are somewhat high, but on statistical grounds it may be conceded that the cacao crop can definitely be expected to benefit from manurial treatment with vegetable mulch, and to a lesser degree by the use of a complete manure.

The chemical composition of the soils of the plots calls for no special comment. It approximates closely to that of an average lowland valley soil as stated in Table I (p. 96).

Tempany's analytical data[18] indicate the magnitude of the gains and losses that have gone on in the soils of the various plots as regards plant nutrients originally present and added as manures, or removed by the plants. In particular, the data, along with further facts brought to light by another investigation[19] show that nitrogen-fixation by bacteria of the *Azotobacter* type is conspicuously active in the soil of the majority of the plots, more especially those that have received vegetable mulch. Tempany specially comments on this high degree of bacterial activity, not only in connection with nitrogen-fixation, but also with regard to the rapid destruction of humus in many tropical soils, and states that the discovery is somewhat unexpected in view of the small content of calcium carbonate of most of the soils, as for example, those of the experiment plots under investigation He accepts a suggestion made by Watts that "under conditions in which the supply of free mineral bases in the soil is deficient, ammonia formed in the process of ammonification may function as a base for the neutralization of nitric acid formed during the later stages of nitrification.' ([18], p. 105; [19], p. 151). We shall have need to refer to this statement later.

The cacao trees occupying the manurial trial plots are, on the whole, in a healthy condition, and yield crops which are considered very high for Dominica. Hence we may assume that the environmental conditions for growth at the Botanic Station are eminently satisfactory as far as the cacao plant is concerned.

The following data which have bearing on the reaction of the soils as one of the factors involved in the growth of cacao, have been brought together from published figures and from the records made by the writer during his own investigations in Dominica.

CACAO PLOTS.

TABLE VI.

Plot.		Manurial Treatment.	Hydrogen-ion concn. pH values.	Percentage of Calcium carbonate.	Lime requirement ($CaCO_3$ per 100 parts of soil).	Deficiency or excess of base. (Comber's test)
Plots on the flat						
1900						
A	Top	Phosphate (basic slag)	7·1	0·124*	...	Excess
	Sub	+ Potash.	7·1	...	...	
B	Top	Organic nitrogen	6·7	0·104*	...	Neither
	Sub	(dried blood).	6·9	...	...	
C	Top	No manure	7·0	0·100*0·081	0·025†	Neither
	Sub		7 1	...	...	
D	Top	Mulch	6 9	0·112*0·107	0·037†	Neither
	Sub		7·1	...	...	
E	Top	Complete manure	7·1	0·104*	...	Neither
	Sub		7·2	...	...	
1907						
F	Top	Mulch	7·0	...	...	
	Sub		7 0	...	...	Neither
G	Top	Organic nitrogen	7·0	...	...	Neither
	Sub	(Cotton seed meal).	7·0	...	..	
Hillside plots						
H	Top	No manure	6·9	...	...	Neither
	Sub		6·9	...	...	
I	Top	Mulch	6·8	...	...	Excess
	Sub		7·0	...	...	
1913						
K	Top	Mulch + Lime (5 cwt)	7·4	0·840	...	Considerable excess
	Sub		7·5	...	...	
L	Top	Nitrolim and organic nitrogen	7·1	...	...	Excess
	Sub	(Cotton seed meal).	6·9	...	...	

*As determined by Tempany in 1915 (19, p. 93); Watts's method was used (22, p. 30).
†As determined by G. A. Jones and recorded by Watts (24, p. 335). The methods used in the determinations were the same as those previously mentiond in this article.

The following conclusions may be drawn from these data.

1. The soil of the plots in the majority of cases possesses a slightly alkaline or neutral reaction. Especially is this fact noticeable in the case of the flat land plots, A to G. Generally speaking, the reactions can be positively correlated with the calcium carbonate content of the soils: It would appear from analyses performed in 1902 (Watts,[22], p. 2), 1915 (Tempany [18], p. 93) and 1920 (by the writer), that the average calcium carbonate content has for many years remained almost constant and at a figure of approximately 0·10 per cent During the past twenty years much calcium must have been removed from the soil by the trees during growth, in the cacao pods which have been harvested, and in calcium nitrate etc. in the drainage water from the plots. The soil does not seem to contain a sufficient reserve of calcium-bearing minerals to maintain the supply of calcium carbonate, for the 1902 analyses [22] indicate that the *total* calcium oxide content of the s il was then of the order 1·2 per cent, which is relatively low. Unfortunately no further estimations of total calcium oxide have been made n more recent years, so that one cannot draw exact comparisons between calcium carbonate content and calcium oxide content for the years subsequent to 1902. It appears highly probable, however, that extra supplies of calcium compounds have been introduced into the soil of the plots from some outside source, and that the most likely source has been and is the drainage water which runs down the slopes of Morne Bruce which borders the plots on the eastern side. This theory has already been advanced in an attempt to explain the reason why the lowland leeward soils in general have a lower acidity than those of the uplands.

The question of the rate of wastage of calcium compounds in the soil is not, however, so simple as it would at first sight appear to be. In certain cases calcium compounds are brought up in the water which moves upwards from the subsoil into the top soil owing to the operation of certain physical forces that are especially manifest in soils of high clay and humus content.

Further, Coville's experiments [2] on the formation of leaf mould indicate that deep-rooted plants can bring about an increase in the total calcium content of the top soil by the fact that their roots extract calcium from the lower soil layers and return it to the top soil in the debris which accumulates on the decay of their fallen leaves. Actual chemical analyses have shown that such a process does go on in many soils that support prolific plant growth.

These two agencies for increasing the calcium content of surface so ls have probably not been very positive in their effect in the case of the cacao soils under consideration. Firstly, these particular soils are of a sandy texture and their water table seldom rises above a depth of eight feet from the ground level even in the rainy season, so that upward movement of water in them is restricted. Secondly, the root system of the cacao plant is not markedly deep-feeding, and probably therefore removes but little nutriant material from the subsoil.

In the absence of further definite experimental data one would perhaps be justified in concluding therefore that the leach-

ing of calcium compounds from the weathered rock of the elevated land that borders the cacao plots maintains a supply of calcium in the soil of these plots sufficient to meet the demand of the cacao trees, and of the reactions that go on in the soil. There would thus appear to be no need to invoke a theory based on the supposition that ammonia liberated in ammonification serves as a base to neutralize acids produced during nitrification to explain the apparently unrestrained activity of nitrifying bacteria in the soil of the cacao plots, as has been done by Tempany (see p. 109).

2. The effects of the manurial treatments on the reaction of the soil solutions of the various plots are clearly shown by the figures for the pH values. Chemical fertilizers have had little or no effect on the reaction, but organic manures have apparently reduced the alkalinity somewhat, especially in the original series of trials (B and D) which have received manurial treatment for twenty successive years.

Numerous investigations have shown that in general organic matter in well aerated soils does not tend markedly to induce an acid reaction (see [6], p 77). Except under conditions of water logging, any acidity that is produced by decaying organic matter is in most cases chiefly due to carbonic acid (*ibid.* p. 46). Mulching in the cacao plots seems to have resulted in a slight augumentation of the calcium carbonate content which is in accordance with the statements made in the last section in connection with the calcium content of leaf-débris.

3. The addition of lime in the form of a small dressing of slaked lime to plot K has resulted in a comparatively large increase in alkalinity. The magnitude of this increase considered in relation to the smallness of the dressing of lime, points to a lack of buffer action (see [6], p. 57) in the soils.

The two soils for which lime requirements have been determined (i. e. C and D) indicate that a greater correlation exists between the pH value and the amount of lime required to correct acidity than between the total carbonate and the lime requirement, for the greater the intensity of acidity in the soil solution, the greater is the lime requirement of these two soils. We have, in fact, in the two soils C and D what is referred to by (Watts [24], p. 337) as 'a curious situation; the so-called acid soils contain carbonates and still are able to neutralize or absorb further quantities of carbonate of lime.' This possibility is not, however, opposed to the results of investigations on acid soils of other regions. It has been fully discussed elsewhere (see [6] 66). to which article the reader is referred for further information.

2. THE LIME PLOTS.

A series of manurial experiments with limes was laid out in 1913 in a narrow valley beyond Morne Bruce and bordering its southern side. Part of the cultivated land had been planted with limes in 1893, but had been allowed to run into bush. Unfortunately the hurricane of 1916 caused so much damage to the trees that the whole series of experiments had to be reorganised and the plots in part replanted.

As at present constituted, the plots are arranged in three series or groups of five plots. Each plot in a series receives a different manurial treatment, so that each treatment is repeated three times. The plots run parallel to each other down the valley and are successively numbered 1, ?, 3, to 15.

Series I. (plots 1 to 5) occurs at the upper end of the valley on land which was originally under garden cultivation, but which at the time of planting the lime trees (in 1913) was in a very bad state. Thorough weeding, followed in 1915 by draining, forking, and the application of small dressings of lime and of organic manure brought the trees into a sound condition. Artificial wind breaks form a necessary protection to the lime trees in this exposed part of the valley,

Series II. (plots 6 to 10) is situated lower down the valley and at its middle portion. It resembles the last in situation and preliminary cultural treatment. The majority of the trees were planted in 1913.

Series III. (plots 11 to 15) includes much of the original land which was planted with limes in 1893. The plots occupy sloping ground which is typical of large areas of lime cultivation in Dominica.

Two other unduplicated plots occur adjoinlng the last series. These may be designated plots 16 (F) and 17 (G). In addition, a large area of land under old lime cultivation occupies the steep slope to the west of Series III. It is not systematically manured however, but receives occasional dressings of vegetable matter. It may be designated plot 18.

The history of the plots and the cultural and manurial treatments to which they have been subjected are fully described in the Annual Reports of the Dominica Botanic Station (1912-20). It is perhaps scarcely legitimate to draw conclusions from the insufficient data so far obtained in the experiments after they were recast in 1916, or to criticise the yield figures on statistical grounds. The following table (Table VI) is sufficient to indicate the tendency of the yield figures and of the productivity of the trees under the conditions of growth presented to them

LIME PLOTS. TABLE VII.

Plot.	Manurial Treatment.	Average annual yield of triplicate series in barrels of limes per acre, for season ending March 1920.	Percentage increase in yield over no-manure plot.
A.	Complete manure.	311 barrels	33·5
B.	Control (no manure)-	233 ,,	—
C.	Vegetable mulch.	268 ,,	15·0
D.	Organic nitrogen (tankage) and phosphate (basic slag).	284 ,,	23·2
E.	Organic nitrogen (tankage) and potash.	243 ,,	4·3
16 (F)	Organic nitrogen (cotton seed meal).	—	—
17 (G)	Vegetable mulch and lime	—	—
18	Occasional mulch.	—	—

The yield figures are very high for the lime crop in Dominica where yields of over 200 barrels to the acre are considered good.

Unfortunately no systematic laboratory examination of the soils of the lime plots has been recorded. The following general description of the soils is taken from the Annual Report for 1919-20 as drawn up by Mr. Joseph Jones.

'The upper part of the valley now under bearing limes is formed of both steep and easy sloping land ; the middle is mainly composed of steep hillsides with a shallow soil, and the lower part (where new trial plots are soon to be laid down) is a little less steep. There are no flat lands.' The soil had been ill-used previously to the inauguration of the experiments in 1913. It had been 'exhausted by peasants' garden crops, baked by the sun, washed by heavy rains and swept by wind.' Subsequent treatment, however, has made the soil highly productive, and 'there appears to be no reason why the soil of this valley should not in time become one of the most fertile spots in the island.'

It may therefore be assumed that at the present day the environmental conditions for growth at the Lime Experiment Station are satisfactory as far as the lime plant is concerned.

During the investigation carried out by the writer, samples of the soils of the lime plots in Series III, Nos. 11 to 18, were taken and the determinations recorded in the following table were made on them after air-drying.

The following conclusions may be drawn from the results set out in Table VII.

LIME PLOTS. TABLE VIII.

Plot.		Soil type.	Manurial treatment.	Hydrogen-ion concn. pH values.	Percentage of calcium carbonate.	Lime requirement. ($CaCO_3$ per 100 parts of soil).	Deficiency or excess of base (Comber's test).
11 (A)	Top	Sandy loam	Complete manure.	6·8	.....	.....	Excess
	Sub			6·8	.....	.....	
12 (B)	Top	Sandy loam	No manure.	6·6	0·033	0·175*	Neither
	Sub			6·6	.....	.....	
13 (C)	Top	Sandy loam	Mulch.	6·5	.....	.....	Slight
	Sub			6·6	.....	.....	deficiency
14 (D)	Top	Clayey loam	Organic nitrogen + phosphate	6·4	.....	.....	Slight deficiency
	Sub		(basic slag)	6·7	.....	.....	
15 (E)	Top	Clayey loam	Organic nitrogen	6·5	.....	.....	Neither
	Sub		+ potash.	6·6	.....	.....	
16 (F)	Top	Clay soil	Organic nitrogen (cotton seed meal).	6·7	.....	.....	Neither
	Sub			6·8	.....	.....	
17 (G)	Top	Clay soil	Mulch + lime.	7·1	.....	.....	Slight
	Sub			7·1	.....	.....	excess
18	Top	Clay soil	Occasional mulch.	6·8	.....	.....	Slight
	Sub			7·0	.....	.....	deficiency

*As determined by G. A. Jones and recorded by Watts (24, p. 335).

1. The soil of all the plots except 17 (G), which receives lime, possesses a slightly acid reaction. There is a slight deficiency of lime in most cases. Appreciable leaching of calcium compounds has apparently gone on, and this can partly be explained by the position of the plots situated as they are on the sides and sloping base of a steep valley.

2. The effects of the manurial treatments on the reaction of the soils are fairly clearly shown. The complete manure, by reason of its content of basic slag, has apparently raised the pH value of the soil solution of plot 11. Mulching has resulted in a slight increase in acidity in each case. Probably the rather large effects in these cases are due to a lack of inorganic buffers in the soils of the lime plots, as in the case of cacao plots last considered.

3. The intensity of acidity in the soils of the plots is apparently not sufficiently large markedly to affect the growth of the lime trees.

(B) OTHER LEEWARD COASTAL DISTRICTS WHERE CACAO AND LIMES ARE GROWN.

It is a noteworthy fact that in the various districts of the leeward coastal region where cacao and limes are grown that the general correlation between high productivity and soil reaction found to hold in the case of the experimental plots of the Botanic Station also applies in those districts that were examined. Thus the best *cacao* soils were found to have a reaction which is approximately neutral, for example Hillsboro (VIII), pH = 7·3; Canefield (XIV), pH = 6·8; Bath (V), pH = 6·7; Pt. Guinard (XII), pH = 6·7, whereas *limes* are apparently growing well on soils of more acid reaction, for example, Bath (IV) pH = 6·5; Soufriere (XXI), pH = 6·4; Clarke Hall (VI) pH = 6·4; Picard (XIX), pH = 5 6.

It would be quite illogical to conclude from these scanty observations that a strict positive correlation exists between the growth of cacao and of limes and soil reaction, for soil reaction is but one of many factors which influence the growth of these plants. It has been shown that there is some relation between tilth and the growth of the cacao tree ([1],[20]). Whether tilth and soil reaction in this case are themselves definitely related yet remains to be proved, and an interesting problem arises out of this coincidence.

(C). THE UPLAND DISTRICTS.

The fertility of the soils of the rainy upland region of Dominica has been discussed in certain publications to which reference has already been made in this paper ([3],[21], [23]). The luxuriance of the forest vegetation in this region has led to the commonly accepted view that the forest soils are exceptionally fertile. In this connexion the remarks of Professor J. B. Harrison in a report on the forest soils of British Guiana are

worthy of careful note. Professor Harrison writes* "The question has been raised as to how it is possible for the British Guiana soils if they are so lacking in fertility, as appears from analyses, to support as they do a heavy forest growth. In the case of a forest, the nutrient constituents of plant food are taken up by roots which traverse a very wide area; in that of cultivated plants, the space occupied by the roots is comparatively small; hence the trees can draw their necessary food from a relatively enormous mass of soil compared to that which the cultivated plants can utilize. The mineral constituents, in the case of the trees, accumulate in the leaves and in the small branchlets, but little being retained in the wood of the stem, and, when the leaves are shed, are in a great part returned to the soil. Similarly, a considerable proportion of the plant food is, in the case of certain trees, returned by the fallen flowers. The plant food thus returned to the soils from which it is derived is set free by the decomposition of the leaves etc., and is again utilized by the trees. Thus the plant food present in the forest soils may be described as circulating and performing its functions in a practically endless circuit from soil through the tree to its leaves and flowers, and, with its leaves and flowers, to the soil. The tendency in the forest is for much of the plant food gathered by the deeper roots to accumulate in the upper layers of the soil In our tropical forests this has taken place in the course of ages to such an extent that the trees which now flourish therein are largely surface feeders so that their roots spread through the thin layers of vegetable débris on the surface soil in a wide extending plexus."

"With the majority of cultivated plants the constituents of the manurial plant food are largely removed in the products, and are thus lost to future generations of plants raised on the same soil. Hence soils capable of supporting a long continued forest growth may, and, as repeated experience here during recent years has amply proved, do, when under economic cultivation, fail after very few seasons to produce crops of any value."

"Further, forest soils appear in many cases to flourish on soil solutions of far lower saline contents than the majority of plants of economic value can do, and it is a matter of interest to plant physiologists to ascertain if this power of assimilating soil solutions of greater diluteness may not be due to the trees growing in symbosis with some of the fungoid organisms with which the upper layers of our forest soils teem."

Professor Harrison has raised many points of interest by these remarks. Of special importance is the composition, concentration and reaction of the soil solutions of tropical soils. Whereas most of the virgin soils as exemplified, for instance, by the soils of the rainy regions of Dominica, are generally not very rich in the so-called reserves of plant nutrients, it must be borne in mind that it is the actual composition of the soil solution and

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* J B Harrison Report on Agricultural work fer 1902 British Guiana. Pt, II, p, 49

not that of the soil itself that is of immediate importance in plant nourishment. The minerals in a soil yield various substances to the soil water, and these are either absorbed by plant roots or leached out in the drainage water. The processes of solution and absorbtion are essentially dynamic and the relative *rates* at which they proceed decides the ability of a soil to maintain a supply of nutrients to the plants it supports.

As Hilgard points out,* it is possible that, under tropical conditions of high rainfall, the rate of decomposition and solution of the mineral nutrients in rocks is so much more rapid than in temperate countries that a soil which, by the usual methods of chemical analysis, appears to be lacking in nutrients may really be highly productive; this of course provided the other numerous factors governing plant growth are favourable.

The question of the calcium supply of plants growing in tropical rain forests is of especial interest. Calcium-ions are absorbed by plant roots and function in some way in precipitating and neutralizing the acidic waste products of metobolism in the plant sap. Each species of plant apparently has its own lime requirement (see [6], p. 68). In regions of high rainfall leaching rapidly removes soluble calcium compounds but plant roots at the same time are competing with it for calcium. In accordance with the dynamic conception of the relation between the soil environment and the plant, it thus becomes apparent that a soil, showing little calcium content when chemically analysed according to the usually accepted conventions, may yet supply the needs of certain plants as far as calcium is concerned. It is possible, however, that only plants of low lime requirements could produce satisfactory growth in soils subjected to excessive leaching. Thus we have here an ecological relationship which may in some measure decide the kind of plant that can thrive in very rainy districts.

The relative unimportance of soil acidity *per se* as a factor in plant growth has been pointed out in the introductory. Unless the hydrogen ion concentration of the soil solution is greater than that represented by a pH value of about 5·0, normal bacteriological processes that ensure a satisfactory nitrogen supply to most plants can go on more or less unchecked in a soil. The acidity of forest soils is, however, frequently much greater than the approximate lower limit stated above. In the upland forest soils of Dominica it has a mean value of about pH 4·6 as indicated by the writer's observations. (Table II). Such a high degree of acidity would be expected to exercise a marked suppression of the activities of bacteria of nitrification and nitrogen-fixation, unless indeed special acid-resisting strains of the bacteria can exist in soils, which would appear unlikely (5). The question of the nitrogen supply of plants growing in acid forest soils is not as far as the writer is aware, yet thoroughly understood. The possibility of ammonium salts serving as the direct nitrogenous food material of plants growing in highly acid soils may furnish an explanation of the difficulty. The bacteria of ammonification can apparently withstand a much greater intensity of

*"Soils." Hilgard, p. 410.

acidity than can the bacteria of nitrification and nitrogen-fixation, so that the production of easily assimilable ammonium compounds from plant residues probably goes on quite rapidly in highly acid soils.

The possibility of the occurrence of mycorhiza growing in symbiosis with the roots of plants that thrive in acid soils must not be overlooked. Their activity does not require that nitrates be present in the soil, for they are apparently able to absorb nitrogenous compounds of some complexity and to pass on elaborated nitrogenous food material to the host plant that harbours them.*

The success of cultivated plants such as the lime tree and cacao that are introduced into newly-opened forest soils may therefore depend either on the ability of these plants to obtain their necessary supply of nitrogen under the peculiar conditions in which assimilable nitrogenous compounds are formed in such soils, or on the degree to which deforested soils can alter under the effects of cultural treatment. The question of the bacteriological content in relation to nitrogen transformation in acid forest soils, and the occurrence or otherwise of mycorhiza on the roots of natural forest plants and on those of plants that are able to adapt themselves to forest soil conditions, would seem to be of special importance in connexion with the development of newly opened forest lands in the tropics. There would appear to be a pressing need for field experiments designed to test the ability of lime trees, etc., to assimilate various forms of nitrogenous food materials. Already there is some indication that ammonium salts stimulate the lime tree to increased activity.

Both the lime tree and the cacao tree possess widely-spreading surface feeding root systems. This would appear to enable them to obtain a sufficient supply of mineral nutrients when growing in soils subjected to considerable leaching.

Furthermore, much evidence has accumulated to indicate that the presence of a thick layer of vegetable mulch on the soil surface is greatly beneficial to their growth (see p. 108). Exactly why this is so has not yet been explained. Newly opened forest lands characteristically possess a large amount of humus which occurs chiefly as a layer of leaf mould on the soil surface.

When these soils are exposed to the action of rain, erosion rapidly ensues and the humus layer is quickly removed. Unless humus is replaced by artificial mulch, one the chief advantages of fresh forest soil is lost, and another inhibiting factor, besides those already enumerated, is introduced.

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*McLean (13) in his studies of the tropical rain forests of South Brazil, noted that the soil of these forests is shallow and pervious, with a water holding capacity of about 40 per cent. and an average water content of 10 per cent. It is deficient in mineral nutrient material, particularly in calcium carbonate. The humus content is about 3 per cent. Mycorhiza is abundantly developed on the roots of the forest trees.

Hesselman (10) has shown that certain types of humus soils formed in Swedish forests are low in mineral nutrients, and exhibit little or no nitrate formation. He concludes that plants growing in such soils must be capable of assimilating nitrogen in the form of ammonium compounds.

Hutchinson and Millar (11) have discussed the general que tion of the absorption by plant roots of ammonium compounds.

The possibility of the presence of toxic amounts of aluminium etc., in the soil solution of the upland soils of Dominica has been alluded to in the discussion of the source of the acidity of these soils. Exactly how far aluminium etc., may act as a limiting factor in the growth of plants in the upland region is not known Nor has the effect which the possible presence of organic toxins exerts on the productivity of these soils yet been fully appreciated. That all these and many other factors should be accurately gauged before any definite opinion is expressed as to the economic possibilities that might follow on the development of the forest areas of Dominica, and indeed of similar areas in certain others of the West Indian Islands would appear to be self evident.

With regard to the particular question of lime cultition in the upland region of Dominica, the experience of planters who are struggling with the difficult conditions that exist there, and the teachings of the valuable data obtained in the plot experiments of the Roseau Botanic Station would seem to indicate that the lime plant flourishes best in soil which is not too acidic, and which contains appreciable amounts of lime. The drainage question in successful lime cultivation is perhaps of greater importance than either of these two factors, but it is intimately bound up with soil aeration, which has been shown in turn to bear a direct relation to acidity and to the formation of toxic organic compounds in the soil.

Finally the incidence and spread of certain fungus diseases in the soil of the upland region and their menace to lime cultivation have been studied in some detail by mycologists attached to the Imperial Department of Agriculture. (see especially Nowell, 3). An acid medium in the majority of cases favours the spread of certain fungi. Any condition which brings about a decrease in soil acidity may be expected in general to reduce disease due to fungi (for example *Rosellinia*), which normally live in soil but which can, under certain conditions, attack living plants. Nowell recommends liming (loc. cit. p. 33), for this reason. Thorough drainage, which increases aeration is also recommended. This would accelerate the destruction of organic substances upon which certain fungi feed in the soil.

Liming to ameliorate the conditions in the Dominica upland region soils is an expensive operation owing chiefly to difficulties of transport. The writer wonders whether or not the finely comminuted volcanic ash (terrace or tarris), found in abundance in most upland districts of Dominica and easy to quarry would not serve a useful purpose in forest soil cultivation. Such material contains a considerable amount of calcium in the form of complex silicates. Under the conditions of rapid weathering which occur in rainy regions, these silicates are undoubtedly quickly decomposed and their calcium rendered available for certain soil reactions that may result in improved conditions for growth. Hartwell and Pember* at the Rhode Island Agricultural Station have recently shown that calcium

* *Soil Science X, 1920, p. 57.*

silicate (Ca_2SiO_4) is able to precipitate active aluminium in soi solutions where this element occurs in toxic amount. Possibly natural calcium silicate minerals, such as occur in tarris might have a similar effect, and trials as to its value as an ameliorant for upland forest soils would thus appear for this additional reason to be greatly desirable.

SUMMARY.

1. The soils of Dominica have been derived from volcanic rocks (lavas, breccias and tuffs) of which the island is mainly composed.

2. These volcanic rocks, as far as is known, consist chiefly of hypersthene andesite and its fragmental equivalents.

3. Grains of minerals such as plagioclase felspars, ferromagnesian minerals and certain accessary and secondary minerals, have been identified in the soils of Dominica. They have been derived from the volcanic rocks by processes of disintegration, weathering and transportation.

4. The variations in the rainfall of the different topographical regions of Dominica have given rise to three main soil types which may be designated (1) Soils of the Central Uplands, (2) Soils of the Windward Coastal Belt and (3) Soils of the Leeward Coastal Belt. The chief chemical characteristics of these soil types are summarized in the text.

5. Lateritization, due mainly to excessive leaching, has apparently gone on to a considerable extent in the wetter districts of Dominica.

6 The Central Upland soils are markedly acid in reaction, owing possibly to leaching which has resulted in an accumulation of alumino-silicic and silicic acids in the soils, together with the formation of soluble salts of aluminum etc. Coupled with this is the possible presence of organic acids in the more water logged and highly humic soils of the upland region.

7. The Leeward soils are approximately neutral in reaction

8. The Windward soils are somewhat intermediate in type.

9. The cultivated soils of the Leeward Coastal Belt are highly fertile to the growth of cacao and limes. Their general characteristics have been studied in some detail, especially in the cacao and lime experimental plots of the Roseau Botanic Station, where the general effect of manurial treatment on the reaction of the soil has been investigated.

10. The soils of the Upland region are pre-eminently interesting because of the luxuriance of the forest vegetation which they support, suggesting as it does an apparent high degree of fertility in these soils. A consideration of the factors which operate in deciding the main features of such forest soils indicates certain peculiar conditions which might not in all cases be favourable to the successful cultivation of plants such as limes and cacao. A complete study of forest soil conditions would appear to be of economic importance in connection with the agricultural development in Dominica and in certain other West Indian islands, of such upland regions of high rainfall.

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